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ORIGINAL PAPER

A PATH TOWARDS A GREENER FUTURE: FOSTERING GREEN SUPPLY CHAIN, GREEN MARKETING, AND ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT. Background: This study contributes to the green supply chain while examining the role of institutional pressure and green marketing to achieve environmental sustainability.
Methods: Data from 256 manufacturing firms in Pakistan was analyzed through a quantitative dyadic data analysis using Structural Equation Modeling by incorporating quota sampling.
Results: The finding revealed that institutional pressures are significantly associated with the green supply chain. The results indicated that green marketing acts as a significant moderator between the green supply chain and customer green purchase intention. Finally, green supply chain practices are significantly associated with environmental sustainability.
Conclusions: This is a novel study that contributed to a green supply chain that integrates all dimensions of the green supply chain in one hybrid model. This study has contributed solid theoretical insights by integrating the theory of planned behavior and institutional theory.

Keywords: Institutional pressures, green supply chain, green marketing, customer green purchase intention, environmental sustainability.

INTRODUCTION

Balancing economic growth and environmental sustainability remains a challenge in the world. In the Asia-Pacific region, including Pakistan, a lack of environmental handling problems and failure to meet the UN's Sustainable Development Goals are reported. The manufacturing sector is a major contributor to environmental pollution in the region and is a significant source of employment and economic growth in Pakistan. However, developing countries lag behind in implementing environmentally friendly processes in their industries compared to developed countries. Companies in developing countries are under institutional pressure and face increased customer demand to incorporate environmental management practices into their operations.

The manufacturing sector of Pakistan significantly contributed to GDP after the agriculture sector. It provides 16.1 % of employment opportunities and contributes 13-14 % to the GDP [Ministry of Finance, 2020]. Large-scale manufacturing counts for 78% of the contribution to manufacturing and has a 9.5 % share of GDP, while small-scale manufacturing contributed 9.5 % to manufacturing and only 2.04 % of GDP [MOF, 2020].

The developed countries took adequate measures to counter these changes, but developing and emerging economies are still far behind [Khan *et al.*, 2017]. Globally, countries have incorporated certain environmentally friendly processes into the production and services industry that help reduce waste [Haq *et al.*, 2016], energy use [Tufail *et al.*, 2021] and enhance resources and reduce the danger to

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human beings and the natural environment [Ma *et al*., 2020]. Achieving sustainable growth is a challenging task for organizations worldwide and especially in developing countries such as China, India, Malaysia, Bangladesh, Pakistan [Khan and Ghouri, 2022].

It is very essential that managers realize the motivating factors for the incorporation of a green supply chain (Green SC) and their substantial impact on sustainability, especially from the perspective of developing nations. Therefore, this study aims to evaluate the antecedents and results of Green SC in context of the role of institutional pressure and environmental performance.

LITERATURE REVIEW

THEORETICAL UNDERPINNING AND HYPOTHESES DEVELOPMENT

The implementation of Green SC among firms is always driven by certain factors that might be motivational, compulsive, or lucrative [DiMaggio & Powell, 1983]. From compulsive factors, certain external elements influence organizations to implement these Green SC, and these might be institutional pressures [Zhu *et al*., 2013]. Furthermore, access to resources and resource allocation may also be the antecedents of the green supply chain among firms [Shi *et al*., 2012]. Therefore, this study defines internal Green SC as the eco-friendly practices implemented, controlled, and managed independently by firms or manufacturers; however, external Green SC are those which usually require the external collaboration of customers and suppliers. The literature indicated that the implementation of both internal and external Green SC results in a higher sustainable performance [Ahmed *et al*., 2019; Khan *et al*., 2021; Samad *et al*., 2021]. These studies also indicated that economic growth can also be enhanced through environmental performance by reducing waste and resource use.

In addition to these antecedents in the implementation of Green SC, certain other factors may also contribute to the improvement of performance measures [El-Garaihy *et al*., 2022;]. However, only the implementation of Green SC is not adequate to get maximum sustainable performance, especially ecological performance [Lee *et al*., 2021]. Similarly, very few studies have highlighted that customer intention and participation are crucial in achieving sustainable organizational performance [Lee *et al*., 2021]. Therefore, an intricate and myriad association exists among antecedents of Green SC, their implementation, customer intention, and organizational performance. To address this gap, a hybrid theoretical model is formulated, while integrating institutional theory [DiMaggio & Powell, 1983] and theory of planned behavior [Ajzen, 1987, 1991].

INSTITUTIONAL PRESSURES AND GREEN SUPPLY CHAIN

The institutional theory states that organizations implement green initiatives and practices for two reasons: compliance with regulations, laws, taxes, and fines, and incentivizing ecological and socially responsible practices [Zailani *et al*., 2012]. Institutional pressures are crucial for the implementation of Green SC, which improves environmental and economic outcomes. The theory supports the link between institutional pressure and the green supply chain.

H1a Coercive pressure significantly influences the internal green supply chain.

H1b Coercive pressure significantly influence on the external green supply chain.

Selection, cooperation, and close ties with suppliers are crucial in incorporating green initiatives in production and manufacturing [Sancha *et al*., 2015]. Coercive pressures play an important role in developed countries in making decisions about suppliers and raw materials [Beske *et al*., 2008; Esfahbodi *et al*., 2017]. External stakeholders, such as customers, suppliers, society, and NGOs, exert normative pressure on the implementation of Green SC [Sancha *et al*., 2015]. In developing nations, normative pressure from suppliers is the main predictor of implementing Green SC [Saeed *et al*., 2018]. In some cases, the threat of copying competitors' practices leads to pressure to implement sustainable suppliers and Green SC [Hoejmose *et al*., 2014]. Implementing an external Green SC promotes environmental sustainability and is associated with better operational performance for companies. Incorporating green practices benefits both organizations and the environment, creating a win-win situation.

H2a Normative pressure significantly influence the internal green supply chain.

H2b Normative pressure significantly influence the external green supply chain.

GREEN SUPPLY CHAIN AND CUSTOMER GREEN PURCHASE INTENTION

Previous literature indicated that customers are not influenced by commercial advertising or promotion through the media [Albayrak *et al*., 2013]. However, the internal green business practices and operations of the firms (such as green manufacturing and green products) can influence customer decisions and, along with the successful implementation of Green SC [D'souza and Taghian, 2005]. The influence of internal ecological practices and ISO certifications on customer behavior has not been widely studied. The combination of external Green SC and green marketing strategies can minimize the ecological impact of business operations. New techniques and values in supply chains can be introduced through customer evaluation of suppliers and return management cooperation.

H3 Internal green supply chain significantly influences customer intention in purchasing green products.

H4 External green supply chain significantly influences customer intention in purchasing green products.

MODERATING ROLE OF GREEN MARKETING

Green marketing is seen as a moderator between Green SC and customer green purchase intention. Green SC refers to the integration of environmentally friendly practices throughout the entire process of production and delivery of goods and services. The role of green marketing is to communicate and promote the green attributes of products and services to customers [Robinot and Giannelloni, 2010]. Green marketing can increase customer awareness and understanding [Zhao and Xie, 2011], and in turn, influence their purchase intention [Khan *et al.*, 2021]. Hence, the moderating effect of green marketing on the relationship between the Green SC and customer green purchase intention highlights the importance of effective green marketing strategies in driving the success of environmentally sustainable business practices.

H5 Green marketing acts as a significant moderator between the internal green supply chain and customer green purchase intention.

H6 Green marketing acts as a significant moderator between external green supply chain and customer green purchase intention.

MEDIATING ROLE OF CUSTOMER GREEN PURCHASE INTENTION

Promoting green initiatives of firms through an eco-friendly supply chain is mandatory to achieve a competitive edge [Beske-Janssen *et al*., 2015; Akhtar et al., 2022]. A Green SC refers to the integration of environmentally friendly practices in the production and delivery of goods and services [Srivastava, 2007]. The customer green purchase intention refers to the likelihood of a customer to choose environmentally friendly products over traditional products [Amin & Tarun, 2021]. Therefore, the role of the firm and the customer in achieving eco-oriented objectives is essential to achieve environmental sustainability [Wolf *et al*., 2014]. When a customer expresses their green purchase intention by choosing a product with a Green SC, this creates a demand for such products, which in turn incentivizes companies to adopt and improve environmentally sustainable practices [Hu *et al*., 2019]. Thus, the customer green purchase intention serves as a mediating factor between Green SC and environmental sustainability.

H7 Internal green supply chain significantly influences environmental sustainability.

H8 External green supply chain significantly influences environmental sustainability.

H9 Customer green purchase intention mediates the relationship between green supply chain and environmental sustainability.

METHODOLOGY

A quantitative data collection technique using primary data. The quota sampling technique was adopted and the units of analysis were dyads, that is, employees and customers. Six major manufacturing sectors were elected on their contribution to production. These include the textile, pharmaceutical, automobile, beverage, chemical, and petroleum sectors. The list of mentioned firms was obtained from Dun and Bradstreet (D&B) and verified from the Chamber of Commerce of all mentioned cities and the All-Pakistan Textile Mills Association (APTMA). The sample size of this study for employees was 256 and for customers was 384. The green marketing measure adopted from Haytko and Matulich [2008], customer green purchase intention from Zhang *et al*, [2017] and institutional pressure, Green SC and environmental performance from Zhu *et al*. [2004,2013]. A quantitative dyadic data analysis approach through Structural Equation Modeling (SEM) was employed since it can handle complex models and run at the same time [Schumacker and Lomax, 2012; Tabachnick *et al*., 2007].

RESULTS

The demographic data results indicated that the majority of the respondents were male (94.4%) and 62.6 % of them were masters. An almost similar number of respondents was between 20-30 (43.2 %) years and 31-40 (39.3%) years. The data was collected through quota sampling and the proportion of respondents based on cities was mentioned in Table 4.1 above. Furthermore, the demographic tables showed that 39.3 % of the managers were supply chain managers of manufacturing firms. The details of others are also mentioned above. The major manufacturing industry contributes 29.9 % of respondents with experience of > 5 years. Details are presented in Table 1.

Table 1 Demographic profile of Managers and Customers

	Managers		**Customers**	
	Frequency	Percentage	Frequency	Percentage
Gender				
Male	291	94.4 %	213	69.1
Female	17	5.6 %	95	30.9
Age				
20-30 years	133	43.2 %	157	51.0
31-40 years	121	39.3 %	105	34.1
41-50 years	38	12.3 %	33	10.7
Above 50 years	16	5.2 %	13	4.2
Education				
Bachelors	104	33.7 %	189	61.3
Masters	193	62.6 %	88	28.6
Post Graduate	11	3.7 %	31	10.1
City				
Karachi	61	19.9 %	93	36.32

Lahore	48	15.6 %	64	25	
Rawalpindi/Islamabad	42	13.7 %	18	7.00	
Faisalabad	38	12.3 %	18	7.00	
Gujranwala	29	9.4 %	12	4.68	
Peshawar	27	8.7 %	11	4.29	
Multan	16	5.2 %	11	4.29	
Quetta	13	4.2 %	6	2.34	
Bahawalpur	9	2.9 %	5	1.95	
Hyderabad	9	2.9 %	10	3.90	
Sargodha	8	2.6 %	4	1.56	
Sialkot	8	2.6 %	4	1.56	
Position			**Industry**		
SC Manager	121	39.3 %	Textile	92	29.9 %
Logistics Manager	68	22.0 %	Pharmaceutical	61	19.9 %
Warehouse Manager	29	9.4 %	Beverages	47	15.2 %
Inventory Manager	39	12.6 %	Automobile	37	12.0 %
Operations Manager	21	6.8 %	Petroleum	37	12.0 %
Q&C Manager	16	5.3 %	Chemical	34	11.0 %
Procurement Manager	14	4.6 %			
Experience					
➢ 5 Years	199	64.6 %			
➢ 10 years	65	21.1 %			
➢ 15 Years	44	14.3 %			

Similarly, the majority of the customers were male (69.9 %) with bachelor's degrees (61.3 %). Among them, 51 % were between the ages of 20-30 years. The quota for customer respondents was calculated based on the population of each metropolitan city, respectively. The majority of the percentage is given to the city with the highest population.

MEASUREMENT MODEL

The reliability of the constructs was assessed using Cronbach's Alpha, CR, and AVE. According to [Hair *et al.*, 2017], values of Cronbach Alpha should be greater than 0.70, CR and AVE should be greater than 0.70 and 0.50 respectively. Cronbach's alpha of all variables is well above the threshold hold. Furthermore, the values of CR and AVE are also well above 0.7 and .50. The values are presented in Table 2.

Table 2 Construct Reliability and Validity

Construct Name	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
CGPI	0.916	0.931	0.628
CP	0.866	0.901	0.603
EGSCM	0.923	0.936	0.574
ES	0.923	0.940	0.722
GM	0.861	0.900	0.643
IGSCM	0.938	0.947	0.617
NP	0.752	0.834	0.502

The desired value of AVE for variables should ideally be greater than the squared correlation R^2 between the specified variable and the other variable [Fornell and Larcker, 1981]. Table 3 showed the discriminant values of each construct. The values highlighted in bold indicate that the square root of AVE is higher than the other values shown in rows and columns. Therefore, the desired different correlations of the construct indicated a good discriminant validity and met the criteria.

Table 3 Discriminant Validity

Variable Name	CGPI	CP	EGSCM	ES	GM	IGSCM	NP
CGPI	**0.792**						
CP	0.033	**0.776**					
EGSCM	0.088	0.452	**0.758**				
ES	0.084	0.488	0.665	**0.850**			
GM	0.729	0.029	0.069	0.046	**0.802**		
IGSCM	0.108	0.490	0.840	0.608	0.108	**0.786**	
NP	0.079	0.551	0.504	0.430	0.117	0.555	**0.709**

STRUCTURAL MODEL

To evaluate the proposed hypotheses and their statistically significant values, structural equation modeling (SEM) was performed. PLS-SEM was carried out using smart PLS 4.0 software by running a bootstrapping resampling method with 5000 subsamples to analyze the statistical significance of the path coefficients. In the structural model, the path coefficients examined the association among the variables [Haenlein & Kaplan, 2004; Hair Jr *et al*., 2017; Kaplan, 2008]. The estimates of path coefficients are shown in Figure 1 and Table 4.

Complete Model Results, Hypothesis Testing, and Path Coefficients

Table 4 Hypothesis Results

Hypotheses	Standardized Coefficients	T-Statistics	P-Values	Results
CP → IGSCM	0.063	4.116	0.000	**Supported**
CP → EGSCM	0.058	4.107	0.000	**Supported**
NP → IGSCM	0.060	6.918	0.000	**Supported**
NP → EGSCM	0.052	7.274	0.000	**Supported**
IGSCM → CGPI	0.084	0.488	0.626	**Not Supported**
EGSCM → CGPI	0.082	1.121	0.263	**Not Supported**
GM x IGSCM x CGPI	0.085	1.989	0.047	**Supported**
GM x EGSCM x CGPI	0.096	2.859	0.004	**Supported**
IGSCM → ES	0.106	2.299	0.022	**Supported**
EGSCM → ES	0.099	4.347	0.000	**Supported**
CGPI → ES	0.040	0.2399	0.811	**Not Supported**

Table 4 shows the results of hypotheses test. The results showed that coercive pressures have a significant positive impact on internal Green SC (β =0.063, t = 4.116, p =0.000). Similarly, coercive pressures are also positively significant with external Green SC (β =0.058, t = 4.107, p =0.000). The normative pressures are also found to have a significant positive association with the internal Green SC (β =0.60, t = 6.918, p =0.000). Similarly, normative pressures are also positively significant with external Green SC (β =0.052, t = 7.274, p =0.000). The relationship between internal Green SC and customer green purchase intention is not significant (β =0.084, t = 0.488, p =0.626). Similarly, the relationship between external GSCM with customer green purchase intention is insignificant (β =0.082, t = 1.121, p =0.263). The moderating role between internal Green SC and customer green purchase intention is found significant (β =-0.085, t = 1.989, p =0.047). Similarly, the moderating relationship between the external Green SC and **c**ustomer green purchase intention was also found to be significant (β = 0.096, t = 2.859, p =0.004). The impact of internal Green SC on environmental sustainability is significant (β = 0.106, t = 2.299, p =0.022). Similarly, the direct impact of external Green SC on environmental sustainability is also significant (β = 0.099, t = 4.347, p =0.000). The impact of customer green purchase intention on environmental sustainability is found to be insignificant (β = 0.040, t = 0.239, p =0.811). Hence, most of the proposed hypotheses were found to be significant at p< 0.05.

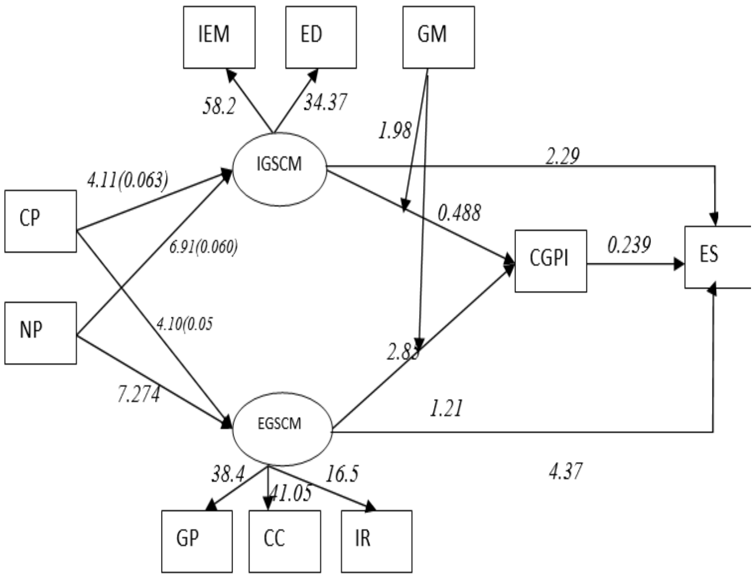

Fig. 1: Path coefficient analysis

Model Fit and Construct Predictive Power

Table 5 R-square and Q Square

Variable Name	Q Square	R Square
CGPI	0.314	0.534
EGSCM	0.227	0.298
ES	0.191	0.451
IGSCM	0.304	0.357

Legend: IGSCM= Internal Green Supply Chain Management, EGSCM= External Green Supply Chain Management, CGPI= Customer Green Purchase Intention, ES= Environmental Sustainability

The fit of the model of the constructs was examined through the coefficient of determination (R^2). The thresh hold values for small, medium, and large predictive accuracy of the proposed model is (<0.25 small), (< .050 medium) and (< .70 large) [Chin *et al*., 2020; Hair *et al*., 2017]. Therefore, the results in the table showed that in this study the predictive power of constructs is medium, since all the R^2 values are above 0.25 and below 0.50. The values of R^2 of all the variables are good enough to predict the accuracy of the proposed model. Similarly, the predictive power of the model has been evaluated through Q^2 the details of the table indicated that the model bears a good predictive power as all values are greater than 0.

MEDIATING ROLE OF CUSTOMER GREEN PURCHASE INTENTION

A mediation analysis was performed to assess the mediating role of CGPI in the relationship between IGSCM, EGSCM, and ES. The results indicated an insignificant indirect effect of IGSCM and EGSCM on ES through CGPI (β=0.000, T=0.103, P= 0.918), (β=0.001, T=0.174, P= 0.862) respectively. The total effect of IGSCM and EGSCM on ES was significant (β=0.243, T=2.299, P= 0.022), (β=0.428, T=4.374, P= 0.000) respectively, with the inclusion of the mediator, the effect of IGSCM and EGSCM on ES was significant (β=0.243, T=2.296, P= 0.022), (β=0.427, T=4.320, P= 0.000) respectively. This shows that CGPI does not play a mediating role in the relationship between IGSCM, EGSCM, and ES. Hence, H_9 was not supported because the indirect effect was insignificant and the direct effect was significant. The results are shown in Table 6 below.

Table 6 Mediating Role of CGPI Between Green SC and ES

Variable Name	Standardized Coefficients	T- Statistics	P-Values
IGSCM--->ES	0.243	2.296	0.022
IGSCM--> CGPI--> ES	0.000	0.103	0.918
EGSCM---->ES	0.427	4.320	0.000
EGSCM-->CGPI-->ES	0.001	0.174	0.862

Note: IGSCM= Internal Green Supply Chain Management, EGSCM= External Green Supply Chain Management, CGPI= Customer Green Purchase Intention, ES= Environmental Sustainability

MODERATING ROLE OF GREEN MARKETING

The moderation results indicated that green marketing significantly moderated the relationship between Green SC and CGPI (β = 0.085, t = 1.99, p = 0.047) so hypothesis 5 was supported. Similarly, the moderating role of green marketing between external Green SC and CGPI was also examined. The results indicated that GM acts as a significant moderator between external Green SC and CGPI (β = 0.096, t = 2.859, p = 0.004), therefore hypothesis 6 was also supported.

Table 7 Moderating Role of Green Marketing

Hypotheses Interaction Variables	Standardized Coefficients	T- Statistics	P-Values	Results
GM x IGSCM x CGPI	0.085	1.989	0.047	**Supported**
GM x EGSCM x CGPI	0.096	2.859	0.004	**Supported**

DISCUSSION

The results of Hypothesis H_{1a} indicated a positive significant association between coercive pressures and internal GSCM; these findings are consistent with the findings of Yang [2018]. The results of $H1_b$ indicated a positive significant association with external GSCM. These findings are consistent with previous studies of [Ali *et al*., 2022; El-Garaihy *et al*., 2022]. However, previous literature on the role of normative and coercive pressures in the adoption of GSCM also contradict these findings [Saeed et al. 2018, Sancha et al. 2015].

The results of $H2_a$ revealed that normative pressures played a significant positive role in internal Green SC. These findings are consistent with previous studies by [Chu *et al*., 2017; Wang *et al*., 2018]. The H_{2b} revealed a strong association between normative influence and external GSCM. These findings are similar to previous studies [Saeed *et al*., 2018].

The results of H_3 and H_4 indicated that IGSCM and EGSCM were not significantly associated with the customer's green purchase intention. Therefore, the association between IGSCM and EGSCM practices and CGPI was found inconsistent with the limited previous studies [Hsu *et al*., 2017; Lee *et al*., 2021]. The contextual difference is the main cause of this inconsistency in results.

The results of H_5 and H_6 indicated that green marketing significantly moderates the relationship between internal and external Green SC and customer green purchase intention. These results are consistent with previous studies [Roh *et al*., 2022,Kao & Du, 2020].

The mediating role of CGPI between Green SC and environmental sustainability has been found to be insignificant, measured through H_9. The direct effect of Green SC and environmental sustainability was also investigated through H_7 and H_8. The results indicated that the internal Green SC has a strong and positive influence on the environmental sustainability of a company. These findings are consistent with [De Sousa Jabbour 2015 and Green et al. 2012], however, partially contradict the findings of [Saeed et al. 2018].

The results of H_9 indicated that CGPI is not positively and significantly associated with environmental sustainability. This relationship has never been witnessed in the GSCM literature, so little is known about the phenomenon.

CONCLUSION

The results of a study showed that green supply chain management in manufacturing firms is influenced by various factors such as institutional pressures, access to resources, and resource allocation. The finding illustrates that coercive and normative pressures have a positive and significant impact on the internal and external Green SC. The relationship between the internal and external Green SC and customer green purchase intention was found to be insignificant. The results of the moderation analysis showed that green marketing significantly moderated the relationship between internal and external Green SC and customer green purchase intention. The results of the study indicate that internal and external Green SC have a positive and significant impact on environmental sustainability, with no mediating role of customer green purchase intention, thus, internal and external Green SC directly result in higher sustainable performance and can enhance economic growth. The predictive power of the proposed model was found to be medium. The results are consistent with previous studies in the field.

THEORETICAL AND PRACTICAL IMPLICATIONS

The study has solid implications for the green supply chain in Pakistan. The results show that environmental regulations are the most influential factor in the implementation of Green SC. Companies must focus on implementing total quality environmental management, cross-functional cooperation, environmental compliance, and ISO14000/14001 certification. In terms of external practices, firms should focus on supplier environmental audits, strong collaboration with suppliers, and sharing product specifications. The results suggest that managers should focus on implementing internal and external GSCM and green marketing to achieve environmental performance. Customers respond positively to green marketing and companies that advertise their products as green. The study also shows that implementing Green SC and attracting customers to green products can lead to improved environmental performance and reduced waste, hazardous materials use, and environmental accidents.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This study has some limitations. First, the data were collected from all large-scale manufacturing firms. Future research can be conducted to obtain data from small and medium firms for a better generalization of GSCM. Second, this study revealed an insignificant index of the moderated mediation of proposed hybrid theoretical model. Therefore, this hybrid model can be tested using mixed research methods that could provide deep insights into the three specified elements. Third, this study has evaluated the most common Green SC implementation, hence future research can be conducted to evaluate the subdimensions of green compliance like environmental auditing and environmental compliance.

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ORIGINAL PAPER

EXPLORING THE INFLUENCE OF IS ON COLLABORATION, AGILITY, AND PERFORMANCE. THE CASE OF THE AUTOMOTIVE SUPPLY CHAIN

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ABSTRACT. Background: Supply chain information systems (SCIS) have turned into a key success factor for the proper management of the automotive supply chain. Therefore, the scope of this paper is to explore the impact of SC information system infrastructure (SCISI) and SC information sharing (ISSC) on interorganizational trust (IOT), SC collaboration (SCC), SC agility (SCA), and SC performance (SCP) in the Moroccan automotive industry context.
Methods: The dataset was drawn from a selected sample of Moroccan automotive industry firms through an online survey. Furthermore, the partial least squares (PLS-SEM) procedure was applied to test the conceptual model.
Results: The findings support the positive influence of SCIS infrastructure on IOT and SC agility. Similarly, information sharing in SC positively affects the collaboration between IOT and automotive SC. The results also provide evidence that IOT plays a significant role in improving SC agility. Lastly, agility and SC collaboration were identified as key drivers of SC of performance.
Conclusions: The findings extend the existing literature on SC management and management information systems by providing empirical verification of how information sharing and IS infrastructure can influence collaboration, agility, and SC performance. These findings are useful in guiding SC managers through the process of improving SC performance.

Keywords: Information systems, information sharing, interorganizational trust, performance.

INTRODUCTION

With a strategic geographical position, a skilled workforce and attractive industrial ecosystems, Morocco has become an African pillar of the automotive industry. This sector has recorded a very notable export performance in recent years. The Moroccan automotive industry has become the leading exporting sector in Morocco [Hahn & Auktor, 2017]. With a contribution of the 16% of gross domestic product (GDP) in 2019, this sector constitutes a driving force of Morocco's industrial development and employment of Morocco's industry.

The automotive industry is driven by a complex demand, in which logistics has a key role to play [Boysen et al., 2015]. Usually, the automotive supply chain is approached in an exhaustive manner by considering, beyond the sole automotive manufacturing, the activity of the production of automotive components and equipment [Frigant & Layan, 2009]. Many players interact within automotive SC, including designers, assemblers, parts suppliers, original equipment manufacturers (OEMs), carriers, and distributors.

In the automotive supply chain, suppliers have increasingly switched to personalization, assuming more responsibility for product design and technology to meet OEM specifications, instead of making ready-made products. In this sense, suppliers began to deliver complete systems; therefore, the responsibility of the first-tier suppliers became assembling entire units. In fact, the role of first-tier suppliers is becoming

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more critical in coordinating with second-party providers.

In the past, there was a deeper integration in the value chain. More particularly, automakers predesigned the respective units and then subcontracted the production of the individual parts to their suppliers, and then assembled them again in-house. This changing division of labour among producers, and in particular their first-tier providers, generated the need for manufacturers to leverage their suppliers' quality systems and production processes to achieve efficiency. As a result, cooperation and long-term partnership between SC members have grown [Thoméet al., 2014].

Faced with challenging upstream logistics and extremely unpredictable demand, collaboration among automotive supply chain members has become a key success factor. This means that the actors in the supply chain, from design to delivery, must collaborate to deliver high-performance logistics services.

In a global market marked by fierce competition, SCIS are becoming essential tools for companies to improve SCM practices in the Moroccan automotive industry. In this regard, the integration of interorganizational information technology is increasingly taking a central place in the automotive Supply Chain. This research seeks to address the potential impact of SCIS on the trust, SC collaboration, SC agility, and performance of the automotive SC in Morocco. In other terms, the question of this research can be formulated as follows: How do information systems contribute to the performance of the automotive supply chain?

This article is structured in the following sections. The first section contains a literature review. The methodology is considered in Section 2. Then, Section 3 is devoted to reporting research findings. Lastly, Section 4 provides discussions and conclusions, highlighting implications, limitations, and perspectives for future studies.

LITERATURE

The automotive supply chain is characterized by the presence of two types of operations: upstream logistics, which serves to supply manufacturing plants, and downstream logistics, which deals with the management of flows between manufacturing plants and the points of sale. Clearly, production sites represent the central point where two logistics issues converge. Upstream, managing production forecasts with precision, in order to guarantee the supply of the factories at all times and at the lowest cost. Downstream, to ensure the delivery of the car to the end customer under the best conditions (cost, quality, lead time, etc.).

Supply chain information system (SCISI)

The functioning of the Supply Chain is based on the complementarity between two kinds of integration: interfunctional and inter-organizational integration. The first revolves around the integration of all logistics processes from upstream to downstream [Tyndallet al., 1998]. Whereas, the second is built around a series of relationships between partner organizations that reciprocally share information, risks, and rewards that lead to the achievement of competitive advantage [Cooper & Ellram, 1993].

For the proper management of logistics operations, enterprises opt for a multitude of information technology systems [Gunasekaranet et al., 2017], such as enterprise resource planning systems (ERP), warehouse management systems (WMS), transport management systems (TMS), and electronic data interchange (EDI). In the present study, we argued that SCIS represent an interorganizational information system, allowing to support cross-border processes within an enterprise (Fig. 1).

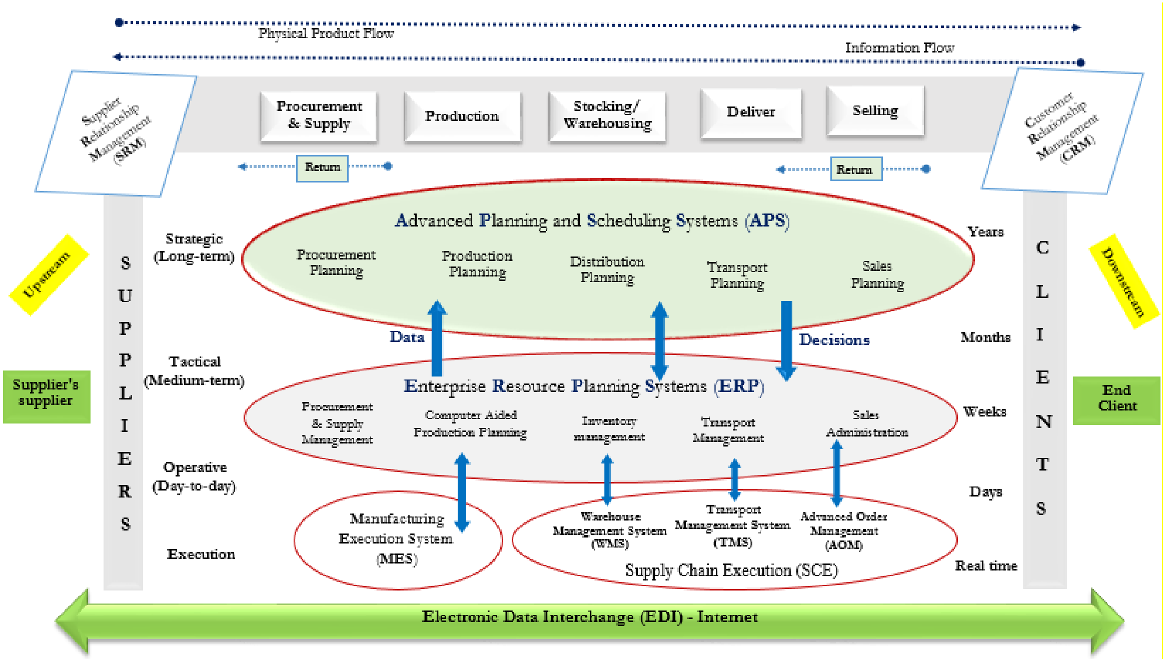

Fig. 1. A framework of IS used in supply chain [Boubker, 2022, p. 61].

The literature has debated the benefits of information technology in the supply chain [Khalid & Omar, 2016]. Information technologies are an essential element to help the supply chain meet changing business demands by reducing overall costs and providing better quality [DeGroote & Marx, 2013]. For example, APS serves as a strategic tool that offers enterprises a solution to achieve several goals at a reasonable cost, in terms of both quality and response time [Jamruset al., 2020]. The ERP system enables the automation of business processes, in turn increasing efficiency and reducing costs for the firm [Oghaziet al., 2018]. RFID technology represents a strategic tool to improve supply chain performance [Ali & Haseeb, 2019]. The EDI system enables coordination among SC partners, which in turn may improve performance and increases the company's competitiveness [Hill & Scudder, 2009]. As explained above, SCIS tools have been identified as an important factor in improving supply chain management practices.

Supply chain information system infrastructure (SCISI)

A large and growing literature has investigated the role of SCIS infrastructure in SC management. Previous studies revealed that the integration of the information system plays an important factor in ensuring a smooth operation of the supply chain by enabling its integration [Liet al., 2009]. IT can also improve the level of interorganizational trust [Chen, 2019], and SC agility [García-Alcaraz et al., 2020; Swaffordet al., 2008]. In sum, technologies facilitate the collection, storage, sharing, and analysis of data [Swafford et al., 2008].

Furthermore, IT integration helps to increase trust among SC members and foster SC agility. For instance [Chen, 2019] put that IT integration into SC contributes to improving the level of interorganizational trust and SC agility. Therefore, we formulate the following hypotheses.

H_1. SCISI has a positive and direct relationship with IOT.

H_2. SCISI has a positive and direct relationship with SCA.

Information sharing (ISSC)

Scientists argued that the use of information technology in SC fosters information sharing [Kim & Chai, 2017]. EDI systems facilitate the exchange of data within the supply chain, allowing the alignment of relationships between partners [Choon Tanet al., 2010]. Information sharing represents a readiness to make strategic and tactical data (e.g., orders, stock levels, forecasts, sales promotion, etc.) available to all supply chain members [Cao & Zhang, 2013b].

In addition, information sharing in SC ensures enterprise survival and facilitate SC integration [Lotfiet al., 2013]. Information sharing provides critical benefits to supply chain members [Kumar & Kushwaha, 2018]. Kim and Chai [2017] argue that information sharing contributes to improved supply chain agility. The IT capacity provides infrastructure for communication and information sharing that promotes collaborative practices within the SC [Fawcettet al., 2011].

The exchange of information among providers and producers can be helpful in responding to uncertainties in the external business environment [Zhou & Li, 2020]. It is inconceivable to ensure coordination between SC members without information sharing [Chen, 2003]. As Fawcett et al. [2011] indicate, a culture focused on information sharing is likely to improve collaboration within the supply chain, contributing to improving operational performance [Fawcett et al., 2011]. Information sharing also promotes SC collaboration and SC integration, and therefore leads to improved supply chain agility [Braunscheidel & Suresh, 2009]. Based on a study among manufacturing companies in India [Afshan, Chatterjee, & Chhetri, 2018] revealed that information sharing and the quality of information significantly affect SC collaboration. Likewise, secure sharing of information improve the level of trust and effective collaboration between SC partners [Panahifaret al., 2018]. From these previous empirical studies, the following hypotheses can be supposed:

H_3. ISSC has a positive and direct relationship with IOT.

H_4. ISSC has a positive and direct relationship with SCC.

Interorganizational trust (IOT)

In recent years, there has been considerable academic and practical interest in the topic of inter-organizational trust [Seppänen et al., 2007]. This concept is defined as "*the extent to which a firm subjectively believes that supply chain partners will perform work and transactions based on its confident expectations, regardless of its ability to check on behaviour or monitor them*" [Cao & Zhang, 2013a, p. 45].

Previous studies have confirmed that trust and technology have a positive and meaningful influence on supply chain collaboration and operational performance [Salam, 2017]. Trust leads to improving the level of collaboration in the supply chain [Panahifar et al., 2018; Uca et al., 2018]. Furthermore, interorganizational trust is an antecedent for commitment, which in turn leads to collaboration among supply chain partners [Afshan et al., 2018]. Likewise, improving the level of trust contributes to improving SC agility [Chen, 2019]. Hence, we assume the following hypothesis:

H_5. IOT has a positive and direct relationship with automotive SCA.

H_6. IOT has a positive and direct relationship with automotive SCC.

Supply chain agility (SCA), SC collaboration (SCC), and SC performance (SCP)

Many studies have identified a number of SC performance predictors [Asamoah et al., 2021; Chandak et al., 2021], including SC agility [García-Alcaraz et al., 2017; Swafford et al., 2008] and SC collaboration [Mofokeng & Chinomona, 2019].

SC agility refers to the response ability of the SC to changing business environments in due course [Al Humdan al., 2020; Kim & Chai, 2017; Shukor al., 2020]. Agility refers to “*ability of an organization’s internal supply chain functions to provide a strategic advantage by responding to marketplace uncertainty*” [Khan & Pillania, 2008, p. 1511]. SC agility can generate business performance [Yusuf et al., 2014], sales growth, profitability, market share, timeliness, and client service [DeGroote & Marx, 2013]. In addition, SC agility improves client value and satisfaction [Gligor et al., 2020] and improve firm performance [Chan et al., 2017]. From the above studies, it is possible to hypothesize that:

H_7. SCA has a positive and direct relationship with automotive SCP.

SC collaboration refers to "*a long-term partnership process where supply chain partners with common goals work closely together to achieve mutual advantages that are greater than the firms would achieve individually*" [Cao al., 2010, p. 6617]. It is recognized that SC partnership, SC collaboration, and integration positively and directly influence SC performance [Mofokeng & Chinomona, 2019]. Likewise, effective collaboration enables SC partners to reduce delivery time, develop distinctive capabilities, improve flexibility, increase client satisfaction, and expand market share and profits [Kumar al., 2017]. Hence, we suggest these hypotheses:

H_8. SCC has a positive and direct relationship with automotive SCP.

The proposed conceptual model includes two independent variables, SCIS infrastructure and information sharing in SC, and four dependent variables, interorganizational trust, SC agility, SC collaboration and SC performance (**Fig. 2**).

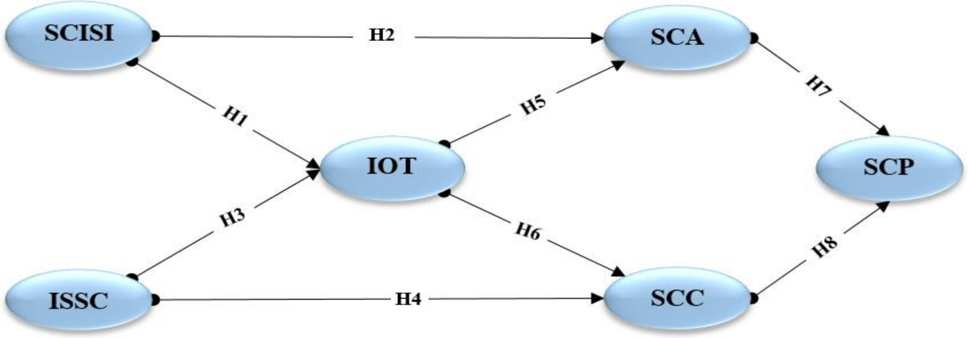

Fig. 2. Proposed research model.

METHODS

The Kingdom of Morocco constitutes a significant manufacturing and export platform for the automobile industry. This sector is a pillar of the Moroccan economy, with many international companies investing in industrial zones, such as the Kenitra Atlantic Free Zone, Tanger Automotive City and Tangier-Free Zone.

Constructs operationalization

The measures used in the current study were selected from the existing literature (Table 1). According to Sundram et al. [2018], SCIS infrastructure has been evaluated using five items. Referring to the study of Kim and Chai [2017], we chose 12 items to measure information sharing in the SC (SCIS). Interorganizational trust (IOT) was measured through six items [Salam, 2017]. SC collaboration (SCC) was measured using five items [Wu & Chiu, 2018]. To measure the agility of SC (SCA), we mobilize the Kim and Chai [2017] scale. Finally, SC performance (SCP) was assessed using six items chosen from Qrunfleh and Tarafdar [2014]. All latent variables were scored according to a seven-point Likert scale, ranging from 1 (total disagreement) to 7 (total agreement).

Table 1. Constructs and measurement items.

Variables	N. of items	Author
SC information system infrastructure (SCISI)	5 items	Sundram et al. [2018]
Information sharing in SC (ISSC)	12 items	Kim and Chai, [2017]
Inter-organizational trust (IOT)	6 items	Salam, [2017]
SC collaboration (SCC)	5 items	Wu and Chiu, [2018]
SC Agility (SCA)	8 items	Kim and Chai, [2017]
SC performance (SCP)	6 items	Qrunfleh and Tarafdar [2014]

Method of data collection and sample size

The sampling frame was composed of a sample of automotive supply chain partners. Because a database of all firms operating in the Moroccan automotive industry is unavailable, we employed a nonprobabilistic method to select the study sample.

This research was implemented in two rounds. As a first step and in order to ensure the relevance of the questionnaire's content, a pilot test of the questionnaire elements was carried out through telephone interviews with two academics and three logistics managers. As a second step, the survey was conducted through a web-based survey between December 2020 and January 2021.

The survey instrument includes two main sections. The first section is devoted to gathering data on the sociodemographic characteristics of the respondents. In the second section, we collect data regarding the latent variables of the conceptual model.

Data analysis method

Regarding the data processing methodology (**Fig. 3),** we used the PLS-SEM method. This decision is motivated by the suitability of this approach to testing complex models, which provides a strong degree of statistical significance using a smaller sample size [Bayonne et al., 2020]. Furthermore, the data set was processed using SmartPLS 3 software [Ringle et al., 2015].

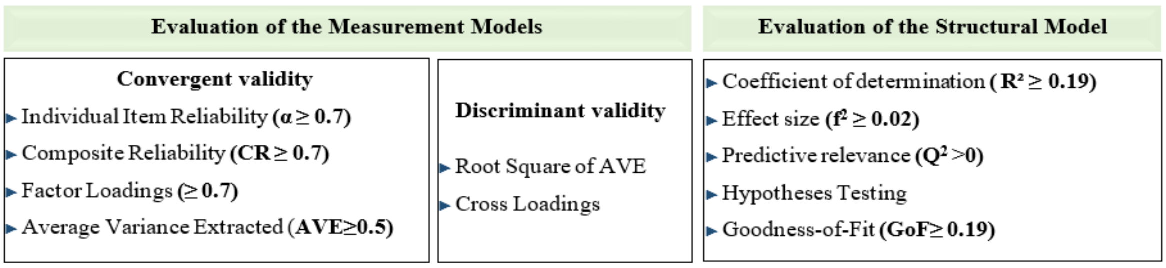

Fig. 3. Stages of data processing [Boubker et al., 2021, p. 7].

FINDINGS

Descriptive analysis

The dataset was compiled by 31 participants from the Moroccan automotive industry, including logistics manager (19.4%), supply planning manager (16.1 percent), logistics customer service manager (12.9%), logistics coordinator (9.7 percent), supply chain manager (9.7%), logistics supervisor (6.5 percent), purchasing managers (6.5%), supply manager (6.5%), demand and supply planner (3.2 percent), logistics director (3.2%), logistics project manager (3.2 percent), and supply chain project managers (3.2 percent). The average age of the respondents is 33 years. Regarding the educational level of the survey participants, 71% held a master's degree (BAC+5), 19.4% had a bachelor's degree (BAC+3), and 6.5% held a Ph.D. Furthermore, more than 70 percent of the theme have gained more than three years of work experience (Table 2).

Based on descriptive statistics, it can be observed that study participants use several IT tools dedicated to SC management in the Moroccan automotive industry, including APS systems, ERP systems (SAP, AS400 and Oracle), EDI, TMS, WMS, SRM, and CRM (Fig. 4).

Results of outer models assessment

The outer models' assessment results provide evidence that the values of all criteria meet scientific standards. The external loading values are all higher than 0.7 (**Fig. 5**), supporting a significant contribution to the model constructs.

Table 2. Study participants' characteristics.

Measure	Category	Percentage
Gender	Female	12.9%
	Male	87.1%
Job Title	Logistics Manager	19.4%
	Supply Planning Manager	16.1%
	Logistics Customer Service Manager	12.9%
	Logistics Coordinator	9.7%
	Supply Chain Manager	9.7%
	Logistics Supervisor	6.5%
	Purchasing Manager	6.5%
	Supply Manager	6.5%
	Demand & Supply Planner	3.2%
	Logistics Director	3.2%
	Logistics Project Manager	3.2%
	Supply Chain Project Manager	3.2%
Education Level	BAC+3 (Bachelor)	19.4%
	BAC+5 (Master degree)	71.0%
	MBA (Master of Business Administration)	3.2%
	BAC+8 (PhD)	6.5%
Work experience	1-3 years	25.8%
	3-5 years	22.6%
	5-7 years	12.9%
	Above 7 years	38.7%

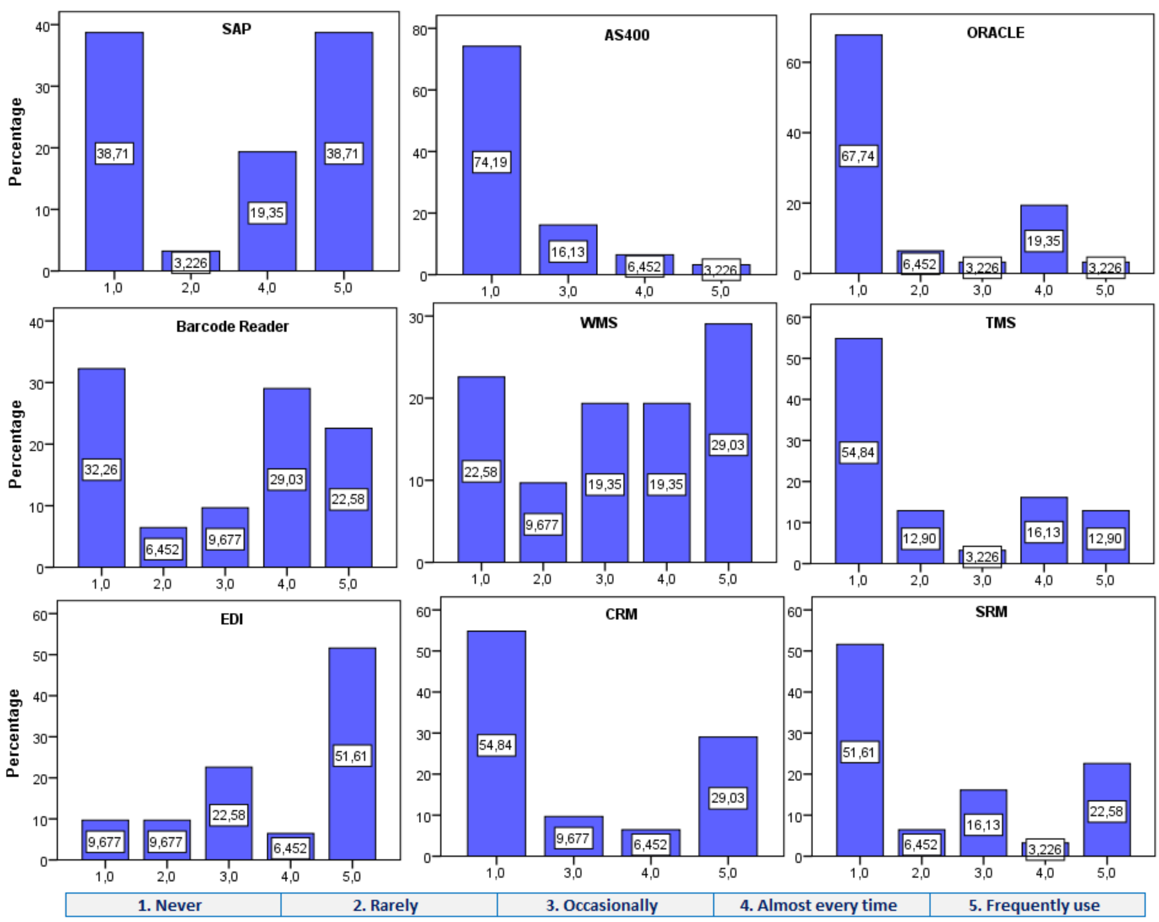

Fig. 4. IT used by the companies surveyed.

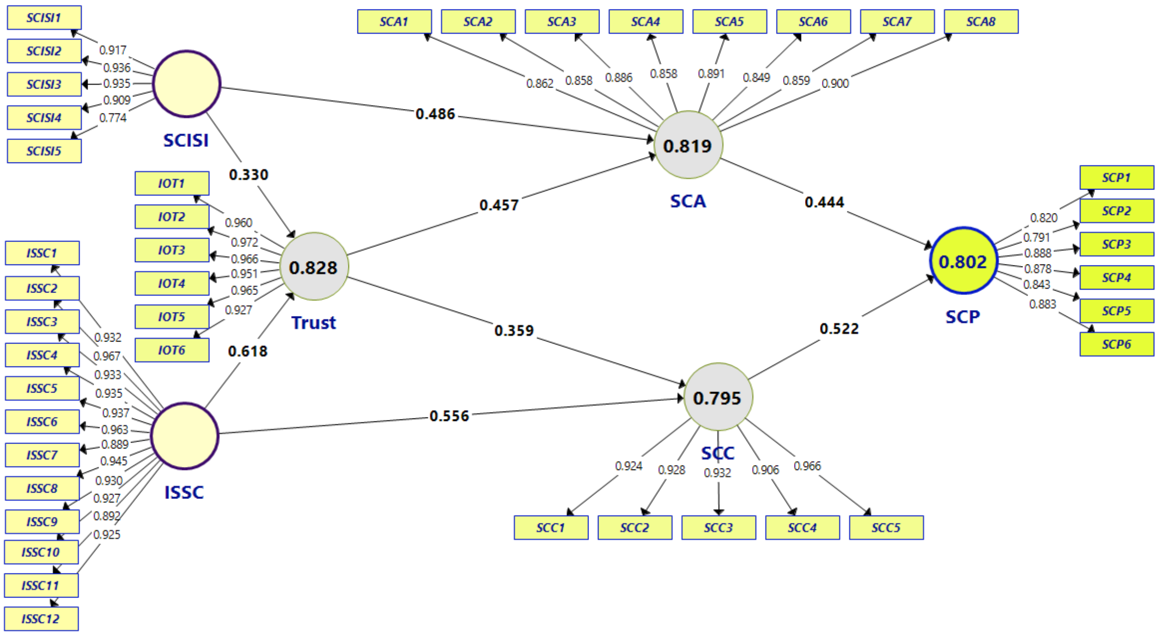

Fig. 5. Measurement model validation.

The AVEs values are all larger than 0.5, meaning that all latent constructs at least provide an explanation of fifty percent of their items' variance [Hair et al., 2019]. Furthermore, both the scale reliability (α) and composite reliability scores are higher than 0.7. Consequently, these results reveal a high degree of convergent validity of the outer model [Boubker et al., 2022]. In addition, the discriminant validity is checked using the Fornell and Larcker criterion (Table 3). Similarly, discriminant validity of the outer models is achieved using the cross-loading criteria (Table 4).

Table 3. Reflective evaluation of the outer model assessment.

Construct	α	CR	rho_A	AVE	ISSC	SCA	SCC	SCISI	SCP	IOT
ISSC	0.986	0.987	0.987	0.867	**0.931**					
SCA	0.954	0.955	0.962	0.758	0.799	**0.871**				
SCC	0.962	0.962	0.970	0.868	0.877	0.718	**0.931**			
SCISI	0.937	0.943	0.953	0.803	0.827	0.870	0.614	**0.896**		
SCP	0.925	0.933	0.940	0.725	0.708	0.818	0.841	0.657	**0.851**	
Trust	0.982	0.982	0.985	0.916	0.891	0.866	0.855	0.841	0.826	**0.957**

Results of assessing inner model

The findings listed in **Fig. 6** support that the R2 values for the four endogenous constructs, trust, SCA, SCC, and SCP are greater than 0.75, which are 0.828, 0.819, 0.795, and 0.802, respectively, demonstrating a robust degree of determination of these variables. It is widely recognised that f^2 values exceeding 0.35, 0.15 and 0.02 are deemed strong, moderate, and weak effect size, respectively [Cohen, 1988]. Accordingly, f^2 of SCIS infrastructure on interorganizational trust, and SC agility are 0.200, and 0.381, meaning that their effect sizes were moderate and strong. Moreover, f^2 of information sharing in SC on interorganisational trust and SC collaboration are strong (0.702) and moderate (0.312). Furthermore, the effect size values of inter-organizational trust on SC agility, and SC collaboration are strong (0.337) and weak (0.130). The f^2 value of the SC agility in SC performance is 0.481, reflecting a large effect size. Lastly, f square of SC collaboration on SC performance is strong (0.666). Furthermore, all Q^2 scores were above zero, showing strong predictive relevance [Hair et al., 2011]. Finally, the calculated GoF value is higher than 0.36, reflecting a great goodness-of-fit of the model [Henseler et al., 2009].

Table 4. Discriminant validity according to cross-loading criteria.

	ISSC	SCA	SCC	SCISI	SCP	IOT
ISSC1	**0.932**	0.742	0.870	0.698	0.695	0.810
ISSC2	**0.967**	0.772	0.916	0.744	0.760	0.871
ISSC3	**0.933**	0.729	0.800	0.802	0.610	0.835
ISSC4	**0.935**	0.747	0.896	0.750	0.730	0.862
ISSC5	**0.937**	0.739	0.835	0.729	0.634	0.765
ISSC6	**0.963**	0.831	0.822	0.862	0.692	0.879
ISSC7	**0.889**	0.716	0.675	0.842	0.493	0.796
ISSC8	**0.945**	0.801	0.769	0.832	0.649	0.887
ISSC9	**0.930**	0.692	0.817	0.752	0.663	0.836
ISSC10	**0.927**	0.764	0.747	0.829	0.650	0.809
ISSC11	**0.892**	0.633	0.791	0.682	0.644	0.781
ISSC12	**0.925**	0.760	0.833	0.735	0.669	0.818
SCA1	0.661	**0.862**	0.621	0.739	0.700	0.774
SCA2	0.684	**0.858**	0.654	0.736	0.725	0.791
SCA3	0.669	**0.886**	0.543	0.777	0.608	0.754
SCA4	0.691	**0.858**	0.627	0.765	0.634	0.741
SCA5	0.791	**0.891**	0.710	0.782	0.794	0.782
SCA6	0.670	**0.849**	0.667	0.688	0.805	0.717
SCA7	0.699	**0.859**	0.582	0.782	0.695	0.715
SCA8	0.694	**0.900**	0.586	0.794	0.720	0.752
SCC1	0.883	0.706	**0.924**	0.676	0.733	0.874
SCC2	0.755	0.635	**0.928**	0.503	0.808	0.762
SCC3	0.733	0.604	**0.932**	0.496	0.840	0.774
SCC4	0.813	0.708	**0.906**	0.578	0.763	0.771
SCC5	0.894	0.690	**0.966**	0.601	0.772	0.798
SCISI1	0.741	0.730	0.440	**0.917**	0.415	0.713
SCISI2	0.809	0.797	0.662	**0.936**	0.698	0.837
SCISI3	0.772	0.823	0.569	**0.935**	0.679	0.764
SCISI4	0.817	0.811	0.664	**0.909**	0.636	0.828
SCISI5	0.537	0.733	0.375	**0.774**	0.485	0.600
SCP1	0.806	0.911	0.738	0.800	**0.820**	0.834
SCP2	0.289	0.407	0.601	0.156	**0.791**	0.422
SCP3	0.631	0.824	0.670	0.679	**0.888**	0.731
SCP4	0.731	0.772	0.786	0.742	**0.878**	0.839
SCP5	0.553	0.520	0.798	0.387	**0.843**	0.640
SCP6	0.467	0.609	0.666	0.401	**0.883**	0.640
IOT1	0.863	0.851	0.823	0.827	0.783	**0.960**
IOT2	0.839	0.832	0.783	0.849	0.767	**0.972**
IOT3	0.860	0.861	0.754	0.851	0.745	**0.966**
IOT4	0.853	0.800	0.857	0.759	0.804	**0.951**
IOT5	0.809	0.794	0.840	0.757	0.811	**0.965**
IOT6	0.888	0.831	0.851	0.784	0.834	**0.927**

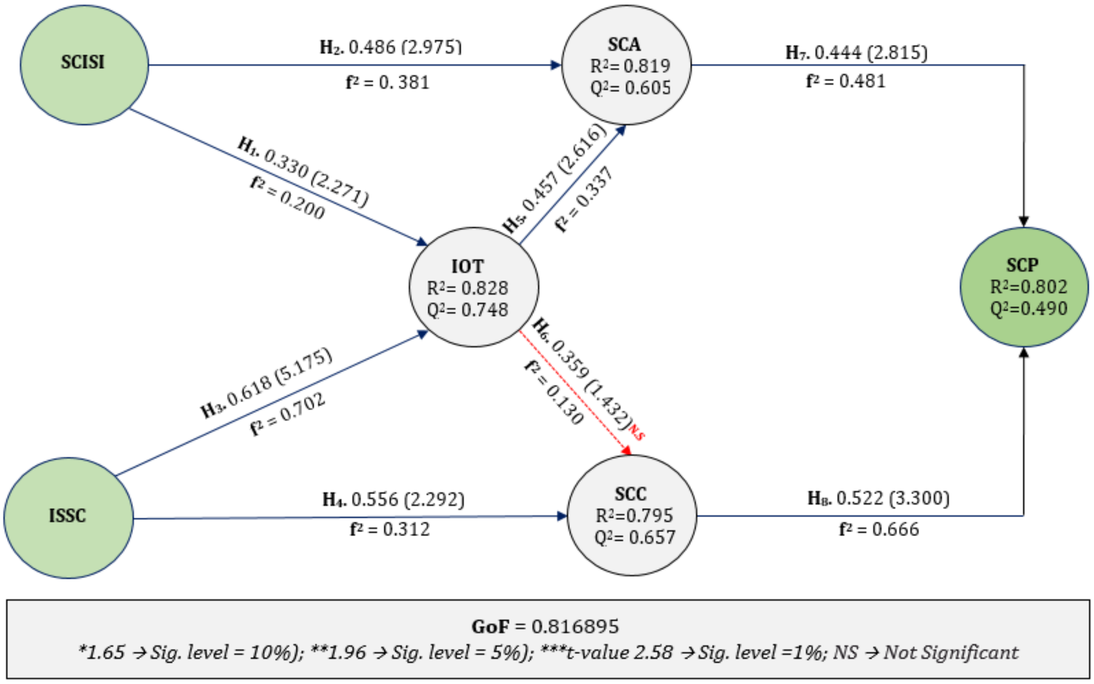

Fig. 6. Results of the model testing.

Based on the PLS-SEM outputs, seven hypothesised relationships were supported, and only one hypothesis was rejected. Thus, H1 was supported (β= 0.330, t = 2.271; p = 0.007), demonstrating a positive influence of the SCIS infrastructure on inter-organizational trust (Fig. 7). The second hypothesis, which stated the positive influence of the SCIS infrastructure on the agility of automotive SC, was found to be statistically significant (β= 0.486; t = 2.975; p = 0.003).

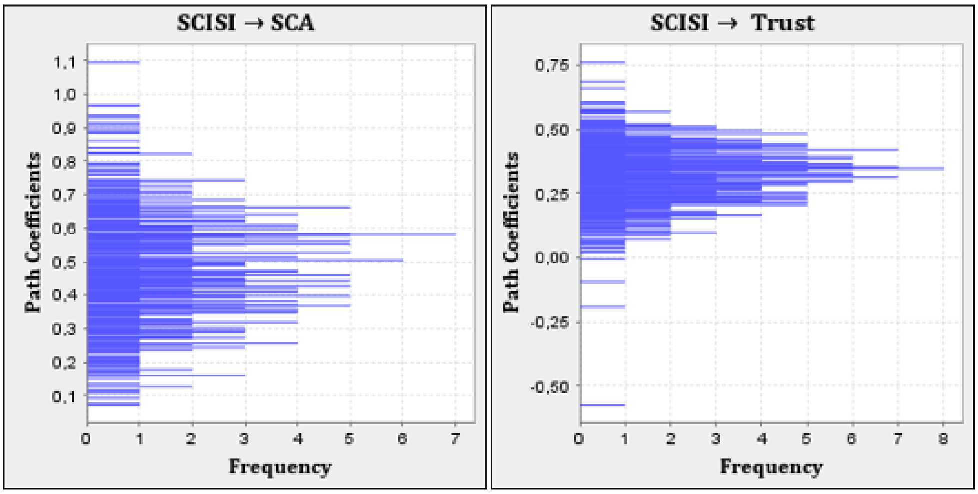

Fig. 7. Path coefficients of SCISI on SCA and IOT - Output SmartPLS.

The findings also supported the third and the fourth hypothesis (Fig. 8), indicating a significant, positive and direct association between information sharing in SC, and inter-organizational trust (β = 0.618; t = 5.175; p = 0.000), and automotive SC collaboration (β = 0.556; t = 2.292; p = 0.022).

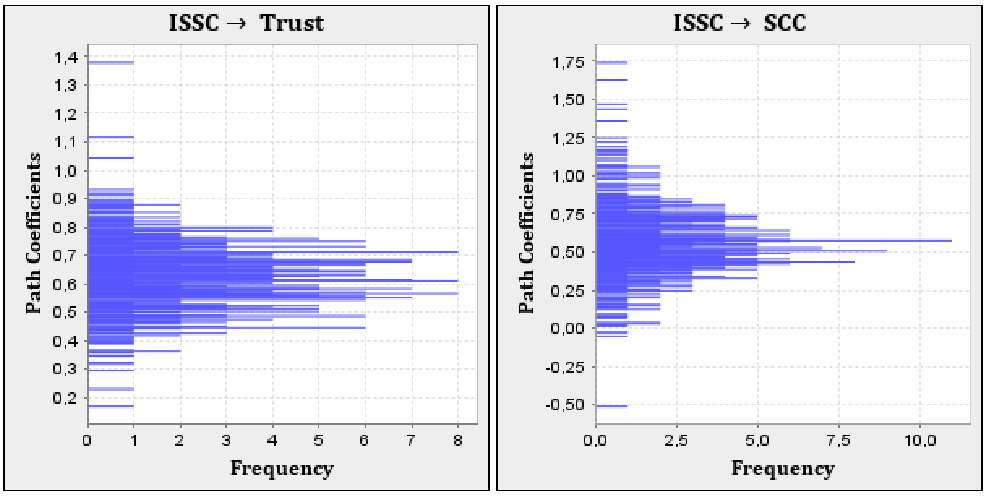

Fig. 8. Path coefficients of ISSC in IOT and SCC - Output SmartPLS.

The fifth hypothesis has also been accepted, indicating a significant association between organizational trust on automotive SC agility (β = 0.457; t = 2.616; p = 0.009). The sixth hypothesis, which claims a positive correlation interorganizational trust and automotive SC collaboration, is statistically not significant (t = 1.432; p = 0.153), which allows us to reject this hypothesis (**Fig. 9**).

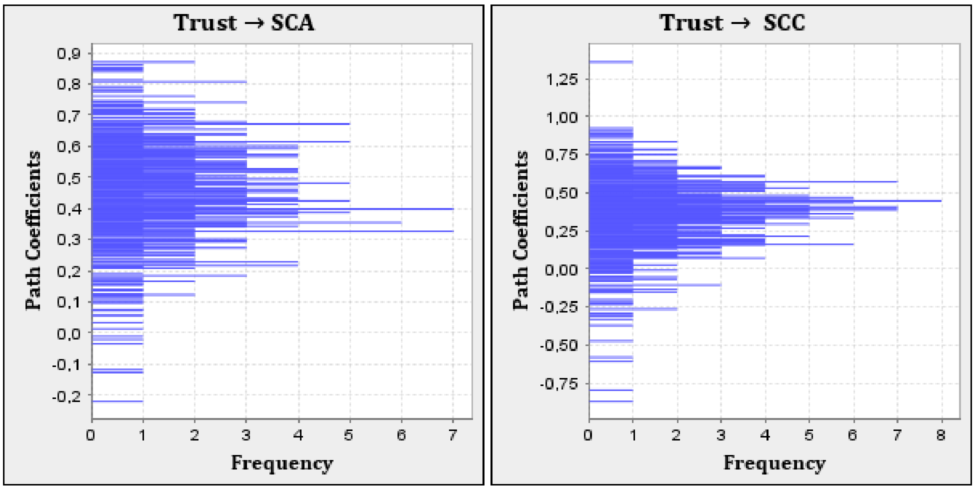

Fig. 9. Path coefficients of IOT on SCA and SCC - Output SmartPLS.

From the PLS analysis (**Fig. 10**), it turns out that automotive SC agility positively and significantly affects automotive SC performance (H_7. β = 0.444; t = 2.815; p = 0.005). Finally, the relationship between SC collaboration and automotive SC performance also receives support from our results (H_8. β = 0.522; t = 3.300; p = 0.001).

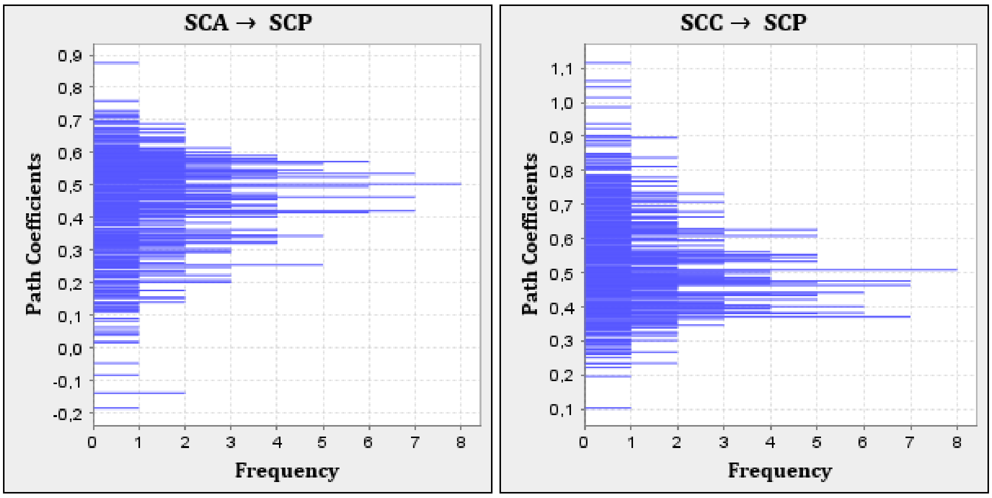

Fig. 10. Path coefficients of SCA and SCC on SCP - Output SmartPLS.

DISCUSSIONS AND CONCLUSIONS

The focus of the current research was to empirically explore the antecedents of SC performance in the Moroccan automotive industry. By employing PLS-SEM, the study findings confirm the positive effect of the SCIS infrastructure in ensuring trust between automotive SC members, and contribute to raising SC's agility level. In other words, automotive SC partners who invested in the SCIS infrastructure (barcode and RFID tags, electronic data interchange) can achieve a significant return on their investment, which strengthens trust among SC members, and further promotes SC agility. These findings were found to be in line with earlier empirical investigations, implying that IT integration helps to build interorganizational trust between SC members [Chen, 2019], and to improve the level of SC agility [García-Alcaraz et al., 2020; Swafford et al., 2008]. With an empirical study of 204 Taiwanese manufacturing firms, Chen [Chen, 2019] showed that IT integration and trust between SC partners strongly improve SC agility and innovation, helping to enhanced company's competitive advantage of the company.

Moreover, information sharing has been shown to reinforce interorganizational trust and to foster collaborative efforts among automotive SC partners. This means that a strategy focused on information sharing and continuous communication between SC actors represents a powerful way to establish interorganizational trust, leading to stronger interorganizational collaboration. As suggested by previous research, secure information sharing among SC partners is a determinant of interorganizational trust and collaboration [Panahifar et al., 2018]. For Indian manufacturing firms, information sharing and its quality were identified as appropriate solutions to increase SC's collaboration level [Afshan et al., 2018]. Furthermore, the results support the positive impact of trust between SC members on the agility of automotive SC. The proof of this hypothesis is consistent with prior studies. For example, Chen [2019] concluded that improving the level of trust between SC partners contributes to improving the level of SC agility.

In contrast to past studies, which highlighted the existence of a positive and indirect link between trust and collaboration [Uca et al., 2018], our findings testify to the lack of a link between trust and collaboration among automotive SC partners.

The findings confirmed the positive effect of SC agility and collaboration between automotive SC partners on automotive SC performance. In this regard, automotive SC parties using practices related to process or product design, and implementation of communication plans, as well as frequent interactions in problem situations, can reap an improved level of performance of the entire supply chain. These results are consistent with previous studies. For example, the study of Blome et al. [2013] carried out with 121 SC professionals shows the presence of a positive link between agility and operational performance. A more recent study showed that collaboration between SC partners improves performance [Mofokeng & Chinomona, 2019].

Implication for theory

In sum, the findings demonstrate that SCIS infrastructure and information sharing provide a basis for enhancing the level of interorganizational trust, collaboration and agility in the automotive SC. Similarly, collaboration and agility also contribute to the explanation of the performance of the automotive SC. Consequently, the current study added value to the literature on SC management. Consequently, the key implication for theory consists in proposing a model specifically appropriate for the context of automotive SC in a developing country, allowing a better understanding of key drivers of SC performance in a particular context.

Implication for practitioners

This research offers certain implications for the practice. The findings highlighted that SCIS infrastructure plays a central role in fostering SC agility and interorganizational trust. In the same way, information sharing between automotive SC members helps to foster interorganizational trust and SC collaboration. Accordingly, we suggest that trust among SC participants should be fostered to achieve agility of the SC, by being able to react to demand fluctuations without overstocking or lost sales, and achieving SC performance.

Another way to improve automotive SC performance consists in ensuring a highest degree of interorganizational collaboration in the automotive industry, by building effective collaborative practices such as designing processes or products, implementing operational activities, and keeping frequent interactions when logistics problems occur.

Furthermore, this study provides automotive SC managers with more understanding of the ways in which SCIS infrastructure, information sharing, trust, SC collaboration, and SC agility can influence SC performance. Hence, automotive SC managers looking to increase SC performance can use these research findings to justify investments in SCIS infrastructure and technologies, i.e., SAPS, ERP, MES, SCE, EDI, barcode, RFID tags.

Study limitations and perspectives

While the current study has provided some valuable practical and theoretical implications, some limitations are present that might be considered in future studies. First, the sample size was smaller than expected, which prevents generalization of the findings. Consequently, increasing the sample size constitutes a recommendation for future work to remedy this limitation. Second, the measurement scales adopted in this research are derived from previous empirical work, without being adapted to the automotive industry. Therefore, a promising direction for future research concerns using an exploratory qualitative approach among automobile company managers, to build measures specifically to the Moroccan automobile industry. Lastly, the implications of the current study are applicable only to the automotive industry. As a future direction, the empirical study can be extended to other sectors, such as the pharmaceutical and aerospace industries in Morocco, in order to generalize the results to these sectors.

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ORIGINAL PAPER

EFFECTS OF GREEN SUPPLY CHAIN MANAGEMENT APPLICATIONS ON OPERATIONAL, ENVIRONMENTAL AND FINANCIAL PERFORMANCE: COMPANY AND FINAL CUSTOMERS

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ABSTRACT. Background: Green supply chain management (GSCM) practices are vital to environmental protection. Many large-scale companies claim that GSCM applications are implemented in their business (with ISO 14001 documents, advertisements, etc.). The purpose of this study is to reveal the relationships between GSCM applications and the operational, environmental, and financial performance of the business. In addition, GSCM practices applied in the business ensure that what is done from the perspective of the final customer. It also determines the external pressures that affect the businesses most in protecting the environment.

Methods: The study consists of two parts. The data in the first part includes the lower, middle and senior managers working in the construction sector operating in Turkey. The data in the second part includes the final customers located in Yenice, Çanakkale**.**

Results: GSCM applications affect the operational, environmental, and financial performance of the business positively. Additionally, similar results were obtained for the final customers. However, there are differences in the degree of impact of both outcomes.

Conclusions: GSCM applications in Turkey protect the environment while searching for the efficiency of the business. However, it seems that the GSCM applications of the business are not fully informed or understood by the final customers. In addition, business employees see that the first factor that will push people to become environmentalists is customer pressure, and the second is the pressure of nongovernmental organizations. The final customers, on the other hand, give priority to environmental awareness first and nongovernmental organizations second. State authority is in the third place.

Keywords: Green Supply Chain Management, Operational Performance, Environmental Performance, Financial Performance, Logistics

INTRODUCTION

Although businesses meet the endless needs and desires of people, they struggle to survive in competitive conditions. Along with the increasing world population, businesses have tended to produce more with the effect of globalization and the development of technology. The world population is expected to increase to 9.2 billion by 2050. This means that production will increase in many areas and natural resources will be consumed more [EU - Green Supply Chain - CE Intelligence Portal, 2022].

While natural resources are consumed in supply chain processes, preproduction and production, the environment is harmed. As in the process before production, carbon emissions are released to the environment due to the heavy use of internal combustion engines in the transfer of products or materials from one place to another in post-production processes. Many scientific studies have been and continue to be done to reduce the carbon emission rate, both in terms of the environment and businesses [Krikella, 2019: 2]. According to world bank open access data, total greenhouse gas emissions [kt of CO2 equivalent] have been increasing rapidly between 1990-2019 [World Bank Open Data, 2022]. This means that the environment is

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rapidly polluted in TZ processes. Pollution causes climate change and drought in the world. According to the May 2022 Global Climate Report, approximately 7% of the Earth's surface reached a record temperature in May 2022, and this is the third highest temperature since 1951. The hottest and the driest month of May was experienced in southern, central, and western Europe with temperatures reaching record levels [https://www.ncei.noaa.gov/access/monitoring/ monthly-report/global/202205,05.07.2022].
Many countries emphasize that environmental protection is not an option but a necessity, by environmental protection agencies. While considering the elimination of poverty in the world through economic developments, the welfare of future generations should also be taken into account [Suansawat, 2013: 1]. Environmental pollution can be the basis for epidemics and natural disasters such as COVID-19, which we live in today and affect the whole world.

GSCM is an emerging field that adds a different perspective from traditional supply chain management understanding. The quality revolution of the late 1980s and the supply chain revolution of the early 1990s encourage businesses to be environmentally conscious. With GSCM, it is aimed at reducing waste in all logistics processes, increasing product-life quality, and protecting natural resources [Mavani, 2015: 20].

GSCM activities have many benefits for companies and society. Businesses acting with the understanding of GSCM can optimize their activities and avoid waste by using their resources (water, energy, materials, natural resources, etc.) in the most ideal way. In addition, businesses can reduce their costs, increase their profitability, produce new environmentally friendly products, create a good image, and increase their level of competition [Zhao, 2016: 6-17]. Some of the benefits for society are clean environment, reduction of climate change, reaching the desired product on time, healthier products or services, reduction of epidemic diseases such as COVID-19, and leaving a good world to future generations.

When the literature in the field of GSCM is examined, organizational, environmental, and financial performance issues are among the leading research. Furthermore, market performance,, financial performance and senior management commitment (Blome et al., 2014; Diab et al., 2015) are among the main topics of GSCM in the field of corporate pressures (Zhu et al., 2013). Also, Chin et al. [2015] conducted studies on environmental cooperation and sustainability performance, Murphy [2012] on the success factors that are the basis for achieving GSCM performance, and Mao [2012] on sustainable development.

One of the most important goals of businesses is to have very good organizational performance. Until recently, organizational performance was divided into financial performance [Feng et al., 2018; Khan, Qianli, 2017] and environmental performance [Seman et al., 2019] and was evaluated in that way. However, studies that are evaluated separately are confusing, inconsistent, and complicated. Furthermore, studies on GSCM performances [Hashmi and Akram, 2021; Feng et al., 2017] are not clearer and more understandable due to being one-sided (business-oriented). Therefore, in the field of GSCM, it is necessary to determine the relationships between variables and conduct more in-depth research, including final customers.

As mentioned above on GSCM, there are few studies on operational, environmental, and economic performance. On the other hand, generally refer to the relationships between performances. Additionally, performance percentages in companies are high. However, there is no study on the determination of the performance status of an exemplary business in GSCM and the evaluation of the business performance of the final customers in this regard.

In this study, the GSCM performances of a large operator in the construction sector are determined. In addition, the status of business performance is determined in the eyes of the final customers. Thus, by determining the levels of relations between the business and its customers, it is revealed what measures should be taken in order to develop relations. Furthermore, in this study, it is ensured that GSCM applications are made in business. GSCM is important in that it raises awareness in a different field, with a different perspective, in the business and in the society, and is the first original research that includes the final customers. For this, the relationships between GSCM applications (environmental management policy (EMP), green purchasing (GP), green marketing (GM), green production (GPR.), green logistics (GL), and green information systems (GIS)) are required for both the business and the customer), and the GSCM performances of the enterprise in the past years (operational performance (OP), environmental performance (EP) and financial performance (FP)) were investigated both in terms of the business and the customer.

The construction sector is one of the most important economic dynamics in Turkey. It affects more than 200 different sectors connected to it [Yavuz, 2019: 2]. The construction sector contributes to the development of the country's economy through the construction of houses, roads, bridges, and dams. With the development of the sector, there is an increase in the rates of gross domestic product, and on the contrary, a decrease occurs [Çınar, 2018: 26]. For these reasons, the construction sector was preferred in our research and the research data were collected by obtaining the necessary permission from the company.

LITERATURE REVIEW

Green Supply Chain Management Applications and Operation Performance

In GSC management, operational performance can be improved by reducing costs, preventing waste, improving the quality of products, and increasing efficiency and productivity. Factors such as delivery times, inventory levels, quality of products and services, capacity utilization rates, and scrap rates are listed as performance metrics. In addition, perceived quality of the products, position of the products in the market, presence of better quality products, the reduction of waste, and the sales in the international market are accepted as operational performance criteria [Lee, 2013: 27].

Businesses are faced with legal and environmental pressure to protect the environment while producing under competitive conditions. Therefore, customers and regulators are constantly pushing businesses to increase their operational efficiency and produce products that protect the environment [Kleindorfer et al., 2005].

Businesses that manage their operational performance well can reduce their costs, increase their profitability, produce new environmentally friendly products, create a good image, and increase their level of competition [Zhao, 2016: 6-17]. In addition to these, they also obtain positive contributions such as safety image, environmental image, image in areas of social responsibility and gaining the loyalty of customers [Çapan, 2008:10-11].

The operational performance measurement factors related to GSCM can be listed as the efficiency of reverse logistics and logistics distribution network, the environmental green image perceived by the society, the green certificates and green image of the suppliers, the compliance of the materials used with ecological design, the green practices in the labeling of the products, the amount of material obtained in recycling, the situation in cooperation with customers and suppliers, the percentage values of the materials that can be recycled, the percentage values of the products determined as waste, the amount of raw materials per product, the amount of energy used per product, the average amount of fuel consumed in vehicle fleets, the amount of pollutants in the air (Günday, 2018: 68-69; Büyüksaatçı, 2009: 30).

Thus, we propose that:

Hypothesis 1: The GSCM applications of the enterprise (EMP, GP, GM, GPR., GL, GIS) are positively related to operational performance.

Hypothesis 2: According to final customers, the GSCM applications of the enterprise (EMP, GP, GM, GPR., GL, GIS) are positively related to operational performance.

Green Supply Chain Management and Environmental Performance

Environmental performance is defined as "the degree to which enterprises improve their performance in accordance with their environmental responsibilities". This performance can be achieved as a result of green practices. Today, performing and monitoring performance studies in SCM activities has become important [Lee, 2013: 24].

The ability of companies to develop environmentally conscious strategies depends on their resources and capabilities. If businesses act according to their strategic business policies and environmental policies, they can use their resources more effectively and efficiently and gain a competitive advantage. In other words, it depends on in-house integration for environmentally friendly production. With environmental policies, while businesses provide economic gains, the consumption of natural resources (mines, air, water, energy, etc.) decreases. If customers and other stakeholders act in environmental cooperation within the SC, the use of natural resources can be reduced by increasing recyclable materials [Suansawat, 2013: 78-80].

There are laws and regulations to protect the environment in Turkey. However, there are no serious targets in the conscious use, re-evaluation, and re-use of resources. Strong state willpower is needed to set serious rules and create policies to protect the environment. In this regard, with the support of local governments, environmental protection cooperation can be achieved among SCM stakeholders. For a more environmentally friendly SCM, the necessary financial resources can be determined and implemented [Toprak, 2017: 190]. Environmental performance is determined by the Department for Environment, Food and Rural Affairs (DEFRA) in 4 main categories (air, water, soil emissions, and resource use) and 22 key indicators. The first category is the waste that each enterprise has left to the environment. These wastes can be hazardous materials as well as recyclable materials. The ISO (International Organization for Standardization) 14001 environmental management system has been developed in order to evaluate and record the environmental performance of enterprises. This ISO-developed criterion can be applied in all kinds of businesses. Additionally, the ISO 14031 standard was developed to guide companies in designing and using environmental performance [Suansawat, 2013: 42-45]. The ISO 14031 standard is based on the plan-do-check-act (PDCA) model. Thus, it creates an infrastructure for continuous improvement and reporting to organizations in areas such as environmental protection, lean production, and sustainable development. The PDCA cycle also forms the basis of the SC management performance system [Shaw and Grant 2010: 327].

Environmental protection activities can provide a sustainable competitive advantage among companies. Some of the benefits of environmental performance to businesses can be listed as providing improvements in costs and productivity, improvements in product quality, increases in market share, more comfortable competitive advantage, increases in employee motivation, and improvements in communication with customers [Zhu and Sarkis, 2004: 269-270].

Thus, we propose that:

Hypothesis 3: The company's GSCM applications are positively correlated with environmental performance.

Hypothesis 4: According to final customers, the company's GSCM applications are positively related to environmental performance.

Green Supply Chain Management and Financial Performance

Businesses must constantly evaluate their financial performance to maintain their assets in a healthy way and make the right decisions. In addition, businesses evaluate their financial performance to reveal where and how much they have spent, what gains they have achieved, and what new investments may be in the future. Since financial performance is a very comprehensive field, studies are carried out in many areas such as accounting, economics, management, and marketing. Traditional and modern metrics are used to measure financial performance. Traditional criteria are accounting content and include studies on the costs incurred as a result of the activities performed. In the modern approach, in addition to the traditional approach, there is a performance measurement based on market conditions. Some researchers who want to measure the financial performance of the business use accounting data by making use of financial statements, while others use data obtained from the market value of the business [Kurt, 2020: 69-71].

The existence of studies in which GSCM-related activities affect financial performance positively or negatively creates uncertainty. However, the source of motivation for GSCM activities is financial factors. The decrease in external costs of the enterprise affects financial performance positively. Competitiveness and company image in GSC management can increase the financial performance of the enterprise by facilitating market entry [Günay, 2018: 70].

Environmental management has a direct relationship with the financial performance of an enterprise. Financial performance is associated with short-term profitability and sales performance [Zhu et al., 2004: 462]. Financial performance is expressed as the financial profit obtained through GSCM activities. The increase in profitability, sales, and economic benefits in market share represent financial performance [Lee, 2013: 28].

Financial performance is one of the priority issues to determine the status of production and service enterprises. Fulfillment of production or services in the desired time and amount is related to the financial power of the enterprises. Financial performance is related to the purchasing of companies, energy consumption, waste management, and legal penalties [Günday, 2018: 69-70].

Thus, we propose that:

Hypothesis 5: The firm's GSCM applications are positively correlated with financial performance.

Hypothesis 6: According to the final customers, the GSCM applications of the enterprise are positively related to the financial performance.

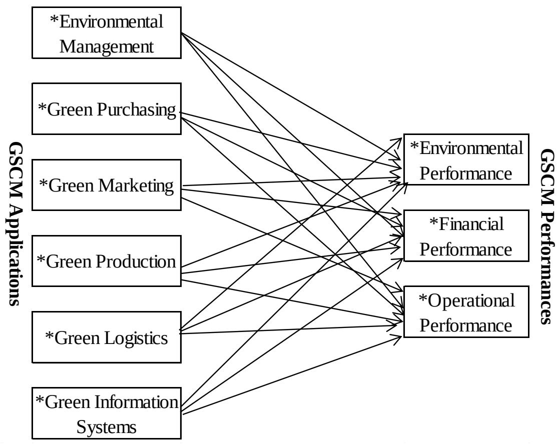

Fig.1. Research model

The model of the study for the business and final customers is shown in Figure 1.

METHODS

Sample and data collection procedure

The data in the first part used in this study consists of lower, middle, and senior managers working in a large business operating in the construction sector in Turkey. The name of the business was not given due to competition conditions. The data in the second part consist of final customers located in Yenice, Çanakkale. The reason why the construction sector is preferred is that one of the most important dynamics of the Turkish economy from 2002 to 2020 is the construction sector and it has relations with more than 200 subsectors. The convenience sampling method was used in both research sections and participation in the survey was voluntary. Data were collected between September and December 2020.

In the first part, an online questionnaire was sent to 200 managers working in the business (under the conditions of the Covid-19 pandemic). The sample size was calculated as 82, with an error rate of 10% and a confidence interval of 90% in a population consisting of 200 managers (lower, middle, and senior managers). 86 participants responded to the online questionnaire and 86 data were evaluated. 26.5% of the participants in this section are women and 73.5% are men. The ratio of undergraduate and graduate graduates is 69.9.

The second part, made for the final customers, consists of people over the age of 18 in Yenice, Çanakkale. To determine the sample size of the data collected face-to-face and online, the sample number was calculated as 134, with 90% confidence interval and 10% margin of error. In the study, data were collected from 288 people. However, as there were inappropriate, unusable, and unanswered questions in 13 questionnaires, they were excluded from the study and 275 data were evaluated. 38.2% of the participants in this section are women and 61.8% are men. The ratio of those who have an associate degree and a bachelor's degree is 58.9. Reliability, frequency, KMO, and correlation analyzes were performed to determine the hypotheses.

Measures

The scales in the study were obtained from Öçlü's [2015] master's thesis. Öçlü coded as "I agree", "Partly agree", "Neither agree nor disagree", "Partly Disagree" and "Disagree" using a 5-point Likert scale. The scale of the study was changed to a 6-point likert, in order to get clearer answers from the survey questions and considering that the participants could give an average answer (Neither Agree or Disagree). The variables in the whole study were measured using a six-point Likert scale ranging from 1 to 6 (1=Strongly Disagree, 2=Disagree, 3=Somewhat Disagree, 4=Somewhat Agree, 5=Agree, and 6=Strongly Agree).

Control Variables

Reliability refers to how much of the measurement tool is free from random errors. Errors can be caused by measurement tools, not understanding the questions, and editing the data. The importance of reliability is that as error rates increase, the confidence in the scale decreases. A reliable scale is one that measures without error. Methods such as test repetition, equivalent forms, and internal consistency methods can be used for reliability calculation. The internal consistency method is used to apply the scale once. The coefficient as a result of the reliability analysis can vary between 0 and 1 numerically. The Cronbach Alpha coefficient is used in the internal consistency method to evaluate reliability. This value is found by dividing the variances of all the variables in the scale by the total variance of the general scale. If this value is less than 70%, the scale is not reliable. However, acceptable scale reliability can be reduced to 60% in exploratory studies [Okumuş, 2018: 242-244]. Reliability analysis results of both survey data were made for the research.

The Cronbach Alpha (α) values obtained according to the analysis results can be interpreted as follows [Öçlü, 2015: 106].

$a < 0.40$	Scale Is Not Reliable
$0.40 < \alpha < 0.60$	Low Confidence Scale
$0.60 < \alpha < 0.80$	Scale Is Highly Reliable
$0.80 < \alpha < 1,00$	High Confidence Scale

Table 1. Reliability results of business and customer data scales

Variables	Number of Items	Measuring range	Cronbach Alpha Coefficient (business)	Cronbach Alpha Coefficient (customer)
EMP	7	6 Likert	0.91	0.866
GP	6	6 Likert	0.884	0.890
GM	7	6 Likert	0.883	0.842
GPR.	5	6 Likert	0.876	0.894
(GL)	4	6 Likert	0.879	0.861
GIS	4	6 Likert	0.911	0.880
EP	6	6 Likert	0.947	0.929
FP	5	6 Likert	0.89	0.884
OP	6	6 Likert	0.884	0.883

As seen in Table 1, the reliability (Cronbach Alpha values) of the data collected from businesses and customers is quite high.

The validity of the data for analysis was evaluated by looking at Exploratory Factor Analysis (Kaiser-Meyer-Olkin) values. Kaiser-Meyer-Olkin (KMO) values range from 0 to 1. If the partial correlation sum is greater than the correlation sum, it means that the KMO value is zero, and this indicates the spread in the correlation model. The reliability of the data increases as the KMO value approaches 1. If the KMO value is 0.5, data analysis can hardly be accepted [Andy 2013: 1974].

Table 2. KMO values of scales applied in the enterprise

Variables	Percentage of variance explained	KMO value	Barlett test	Number of component factors	sd value	p value
EMP	64.971	0.861	359.30	1	21	0.000
GP	65.197	0.814	298.77	1	15	0.000
GM	60.177	0.861	294.21	1	21	0.000
GPR.	67.050	0.852	203.66	1	10	0.000
GL	73.741	0.744	194.93	1	6	0.000
GIS	79.302	0.790	248.82	1	6	0.000
EP	79.088	0.903	463.56	1	15	0.000
FP	69.679	0.794	276.40	1	10	0.000
OP	63.89	0.834	263.64	1	15	0.000

The KMO analysis results of the business and customer data are given in Table 2. In the analysis, multiple variables were gathered under a single factor and the variance and KMO values were close to 1. Additionally, since the "p" value is less than 0.05, the data are in good condition for analysis and the analysis can be continued.

DATA ANALYSIS AND RESULTS

Descriptive Statistics and Correlation Analysis

Descriptive statistics and correlation analysis results for enterprise data are given in Table 3.

According to the results of the correlation analysis matrix in Table 3, the "r" and "p" values between the GSCM applications of the enterprise (EMP, GP, GM, GPR., GL, GIS) and the operational, environmental and financial performance are significantly and positively related. According to the final customers, it is seen in the matrix in Table 4 that the "r" and "p" values between the GSCM applications of the enterprise (EMP, GP, GM, GPR., GL, GIS) and the operational, environmental and financial performance are significant and positive. In this case, hypotheses H2, H4 and H6 are supported. The strongest positive relationships in the matrix are between GIS – OP (r=.524**, p< 0.000) and GL – OP (r=.503**, p< 0.00).

DISCUSSIONS AND CONCLUSION

There have been many studies on financial and operational performance in different countries on green supply chain management [e.g. see, Hashmi and Akram, 2021; Feng et al., 2017]. However, there is a lack of clear information and evidence on how GSCM practices directly and indirectly affect their operational, environmental, and financial performance [Golicic, Smith, 2013].

In this study, the relationships and severity of the relationships between the business and final customers GSCM applications and the operational, environmental, and financial performances of the business were determined. Furthermore, external pressures and their importance levels for green activities in terms of businesses and customers were determined. The results of the study support the hypotheses formulated. The first and second hypotheses of the study, according to the business and the final customer (H1 business, H2 customer), have been confirmed that GSCM applications positively affect the operational performance of the business. There are differences between the effect levels of both results. Although the results of the first processing are close to each other, the greatest effect is between GP-OP (r=.518**, p< 0.00). Similarly, although the final customer results are close to each other, the most impact is between GIS-OP (r=.518**, p< 0.00). Hashmi & Akram [2021], Feng et al., [2017] and Jawaad & Zafar [2019] found a positive relationship between GSCM and operational performance, similar to this study. Furthermore, in this study, the employees of the company believe that the most important factor that increases the operational performance is the GP. Final customers, on the other hand, believe that the green information system contributes more to operational performance.

The third and fourth hypotheses of the study, (H3 enterprise, H4 customer), according to the enterprise and the final customer, were confirmed that GSCM applications positively affect the environmental performance of the enterprise. There are differences between the effect levels of both results. The most effect on the results of the processing is between GPR.-EP and GIS-EP (r=.739**, p< 0.00). Similarly, Kumar et al. [2019] and Rao and Holt [2005] determined that green supply chain management is an element that reduces environmental pollution and increases the efficiency of the enterprise that protects the environment. Furthermore, although the final customer results of the customers are close to each other in this study, the most impact is between GIS-EP (r=.466**, p< 0.00). In this case, while the employees of the company believe that the most important element that increases environmental performance is the GPR., the customers believe that the green information system contributes more to environmental performance.

Table 3. Correlation matrix of enterprise performance with GSCM applications

	Variables	EMP	GP	GM	GPR.	GL	GIS	EP	FP	OP
EMP	Pearson Correlation	1	.572**	.584**	.571**	.606**	.680**	.728**	.523**	.457**
	Sig. (2-tailed)		.00	.00	.00	.00	.00	.00	.00	.00
GP	Pearson Correlation	.572**	1	.754**	.540**	.688**	.515**	.480**	.417**	.518**
	Sig. (2-tailed)	.00		.00	.00	.00	.00	.00	.00	.00
GM	Pearson Correlation	.584**	.754**	1	.621**	.683**	.584**	.626**	.522**	.501**
	Sig. (2-tailed)	.00	.00		.00	.00	.00	.00	.00	.00
GPR.	Pearson Correlation	.571**	.540**	.621**	1	.727**	.686**	.739**	.584**	.507**
	Sig. (2-tailed)	.00	.00	.00		.00	.00	.00	.00	.00
GL	Pearson Correlation	.606**	.688**	.683**	.727**	1	.628**	.561**	.504**	.475**
	Sig. (2-tailed)	.00	.00	.00	.00		.00	.00	.00	.00
GIS	Pearson Correlation	.680**	.515**	.584**	.686**	.628**	1	.739**	.578**	.492**
	Sig. (2-tailed)	.00	.00	.00	.00	.00		.00	.00	.00
EP	Pearson Correlation	,.728**	,.480**	,.626**	,.739**	,.561**	.739**	, 1	,.556**	,.685**
	Sig. (2-tailed)	.00	.00	.00	.00	.00		.00	.00	.00
FP	Pearson Correlation	,.523**	,.417**	,.522**	,.584**	,.504**	.578**	, .685**	, 1	, .672**
	Sig. (2-tailed)	.00	.00	.00	.00	.00		.00	.00	.00
OP	Pearson Correlation	,.457**	,.518**	,.501**	,.507**	,.475**	.492**	, .556**	, .672**	, 1

Sig. (2-tailed)	.00	.00	.00	.00	.00		.00	.00	.00

(**) The correlation shows that it is significant at the 0.01 level.

Table 4. Correlation matrix of enterprise performances with GSCM applications according to final customers

Variables		EMP	GP	GM	GPR.	GL	GIS	EP	FP	OP
EMP	Pearson Correlation	1	.718**	.502**	.503**	.562**	.528**	.446**	.350**	.423**
	Sig. (2-tailed)		.000	.000	.000	.000	.000	.000	.000	.000
GP	Pearson Correlation	.718**	1	.585**	.573**	.552**	.538**	.422**	.364**	.386**
	Sig. (2-tailed)	.000		.000	.000	.000	.000	.000	.000	.000
GM	Pearson Correlation	.502**	.585**	1	.717**	.668**	.623**	.305**	.339**	.396**
	Sig. (2-tailed)	.000	.000		.000	.000	.000	.000	.000	.000
GPR.	Pearson Correlation	.503**	.573**	.717**	1	.773**	.670**	.381**	.383**	.443**
	Sig. (2-tailed)	.000	.000	.000		.000	.000	.000	.000	.000
GL	Pearson Correlation	.562**	.552**	.668**	.773**	1	.751**	.462**	.399**	.503**
	Sig. (2-tailed)	.000	.000	.000	.000		.000	.000	.000	.000
GIS	Pearson Correlation	.528**	.538**	.623**	.670**	.751**	1	.466**	.411**	.524**
	Sig. (2-tailed)	.000	.000	.000	.000	.000		.000	.000	.000
EP	Pearson Correlation	.446**	.422**	.305**	.381**	.462**	.466**	1	.647**	.730**
	Sig. (2-tailed)	.000	.000	.000	.000	.000		.000	.000	.000
FP	Pearson Correlation	.350**	.364**	.339**	.383**	.399**	.411**	.647**	1	.626**
	Sig. (2-tailed)	.000	.000	.000	.000	.000		.000	.000	.000
OP	Pearson Correlation	.423**	.386**	.396**	.443**	.503**	.524**	.730**	.626**	1
	Sig. (2-tailed)	.000	.000	.000	.000	.000		.000	.000	.000

The fifth and sixth hypotheses of the study, (H5 enterprise, H6 customer), according to the enterprise and the final customer, were confirmed that GSCM applications positively affect the financial performance of the enterprise. There are differences between the effect levels of both results. The most effect on the results of the processing is between GPR.-FP (r=.584**, p< 0.00). Similarly, Rao and Holt [2005] and Zhu et al. [2013] reported that green practices have a positive relationship between profitability and financial performance of enterprises. Furthermore, although the final customer results are close to each other in this study, the greatest effect is between GIS-FP (r=.466**, p< 0.00). In this case, the most important element that increases the environmental performance of employees is the GPR. while customers believe that the green information system contributes more to environmental performance.

In addition to these, Hashmi and Akram [2021] found the highest level of relationship between GSCM and FP (r=.680**, p< 0.01) in their study between GSCM and OP, EP and FP for businesses. In this study, the highest relationship level in terms of business is GIS and GPR. and EP (r=.739**, p< 0.00). Unlike other studies, to protect the environment, it is necessary to reduce environmental waste in environmental performances and spread environmental awareness more than activities aimed at reducing costs in financial performances in this study.

In summary, in this research conducted for businesses and final customers, the GSCM applications of the business are not fully informed or understood in terms of final customers. While the enterprise effect of the GSCM applications on the performance of the enterprise is high, the final customers are low. Additionally, as a result of frequency analysis, while the company's employees believe that environmentally friendly works are sufficient, the final customers believe that environmentally friendly work should be increased. Furthermore, the most recyclable material in the enterprise was determined as "plastic", while the final customers mentioned "cardboard". In this respect, the GSCM activities implemented in the enterprise will be able to contribute more to the image and profitability of the enterprise by informing the final customers.

In addition to the business differences between the results and the final customer, the similarities are as follows. In both, recycling bins are at the forefront of the most important waste facilities. All parties should act with understanding of GSCM in the prevention of epidemics.

Factors that will push people to be environmentalists (customers, non-governmental organizations, state authority, competitors, and environmental awareness) see the first as customer pressure and the second as the pressure of non-governmental organizations. The final customers are environmental awareness first, and nongovernmental organizations second. This situation shows that while businesses evaluate the environment according to self-harm, end customers think more about environmental issues.

The necessary trainings should be increased in terms of final customers, environmental protection, and raising awareness. With the environmental awareness that will be formed in society, businesses will focus able to be more directed towards green activities. For a more environmentally friendly SCM, state authorities need to provide more solidity and act in cooperation with businesses. Businesses can be encouraged to be more innovative and act with environmental awareness.

One of the most important limitations of the research is that the study was carried out in the Covid-19 pandemic outbreak. Due to the pandemic, it was not possible to reach more participants. However, the minimum data collection levels that can represent the main population have been reached. In face-to-face data, the possibility of misunderstanding or incompleteness of the subject explained to the final customers by wearing a mask is another limitation. In addition, while some of the people participating in the survey answer the questions, there may be measurement errors due to the possibility of choosing the ideal rather than the current situation. In addition, choosing a company from among existing industrial establishments is another constraint.

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ORIGINAL PAPER

DIGITAL TRANSFORMATION OF SUPPLY CHAINS AND COMPANY'S PERFORMANCE

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ABSTRACT. Background: The aim of the article is to examine the determinants of the digital transformation of the supply chains (DSCs) of companies. The presented research covers the stages of digital supply chain transformation, applied key technologies, and the results of implementation of DSC transformation.

Methods: The research covered 235 randomly selected Polish companies of all sizes, focusing on transport and warehouse management companies (33.6%), industrial processing (15.7%), other services (11.4%) and wholesale and retail trade (11.1%). Data were acquired by the CAWI method in 2022. For statistical calculation, Pearson correlation and factor analysis were used.

Results: The results of this paper indicate that the DSC transformation process is implemented with rather similar and moderate degree of intensity (mean 3.61 on a scale from 1 to 5). The transformation process of DSC is based on several interdependencies, that is, between integration of company's technology base and other entities of the supply chain as well as with scale and improve the solutions for DSC. Moreover, DSC transformation is positive related with all of the performance measures (profit, sales, market share, ROI, and competitive advantage), while the greatest increase is noticed for ROI. Furthermore, the factor analysis confirm that a systematic and comprehensive approach to the transformation of DSC raises company performance.

Conclusions: The presented research allows for a better understanding of analysed variables and the context that determines DSC transformation for both managers and practitioners. Thus, it enable building a strategy and roadmaps for the digital transformation of enterprises and mitigate associated risks.

Keywords: supply chain, digital supply chain, transformation, process, performance

INTRODUCTION

Innovation is one of the key factors that ensures a competitive advantage for enterprises that carry out activities related to introducing changes in their business model [Dymitrowski and Mielcarek 2021]. However, maintaining a high level of innovation in an environment characterised by discontinuity and violent shocks is becoming a growing challenge.

In the face of changes, it becomes increasingly difficult to improve profitability and maintain the effectiveness of supply chains. To put this in a simple formula, supply chain management is about "having the right item in the right quantity at the right time at the right place for the right price in the right condition to the right customer" [Mallik 2010]. As a result, there is increasing requirement for improving sustainable outcomes in the supply chains that based on integrating social, economic and environmental goals of focal company [Carter and Rogers 2008]. Moreover, there are some raising challenges for managing global supply chains concerned with limited visibility and control over scattered between different geographies and multiple business tiers supply chain entities [Choi and Hong 2002, Koberg and Longoni 2019]. One of the directions that can mitigate these threats and meet raising demands of stakeholders is the digital transformation of supply chains [Ageron et al. 2020, Preindl et al. 2020].

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Despite the relatively low advance of the digital transformation of supply chain, forecasts show that this will be one of the key trends in the next five years for many industries, with more than 90% of respondents expecting more process automatization and receiving real-time status updates from the entire supply chain [CapGemini 2016]. Therefore, taking into account frequent and rapid disturbances in the environment and the growth of ICT technology development, interest about digital transformation is increasingly increasing both among theoretical and practical specialists. Digital supply chains (DSCs) are not only more responsive to changes in the business environment than a traditional supply chains, but also they increase transparency for entities across the whole supply chain that support better decision making and communication [Preindl et al. 2020]. The digital supply chain can be defined as 'development of information systems and the adoption of innovative technologies that strengthen the integration and the agility of the supply chain and thus improve customer service and sustainable organisation performance' [Ageron et al. 2020, p. 133]. Another definition of DSC by Kinnett is: 'an intelligent, value driven network that leverages new approaches with technology and analytics to create new forms of revenue and business value, through a centric platform that captures and maximises the utilization of real-time information emerging from a variety of sources.' [2015]. This can be seen as a deep and extensive change in supply chain management and therefore also a challenging project in terms of organisational development process. According to Sabri, Micheli, and Nuur, DSC implementation is a long-term cyclic process with phases that transform interorganisational and cross-functional relations of organisation [2018].

Taking into account the various conditions of DSC transformation, the aim of the article is to examine and describe the determinants of digital transformation of the supply chains of Polish companies. Therefore, it is worth formulating a number of questions that will allow one to broaden the knowledge about this phenomenon in relation to Polish companies:

What is the stage of the digital supply chain transformation process?

Are there any interdependencies between activities of the DSC transformation process?

What are the most relevant elements (technologies) of DSC transformation?

Are there any interdependencies between elements (technologies) of the DSC transformation?

What are the results of the digital transformation of the supply chain for the company's performance?

THEORETICAL BACKGROUND

One of key drivers of digital transformation is the fourth industrial revolution that uses cyber physical systems provided with heterogeneous data and integration of knowledge, which allows to create smart (intelligent) products, apply 3D printing, and use of artificial intelligence, i.e., in autonomous vehicles or smart factories [Hendler 2019]. This change the elements, flows, processes and network structure of the supply chain by pushing towards a new way of management including evolution into merging physical and digital operations within a physical and virtual world [Garay-Rondereo et al. 2020, Cyplik, Zwolak, 2022]. Taking advantage of new technologies within supply chain and the introduced concept of Industry 4.0 will be dependent on establishing full-scale smart infrastructure allowing merge of data, physical objects, products, together with processes [Wu et al. 2016, p. 395-396]. Wu et al. define smart supply chain as the new interconnected business system that extends from isolated, local, and single-company applications to systematic smart implementations [2016, p. 396].

Digital transformation may mean varying degrees of interference in the architecture of the elements that make up the business model and the way it functions. Literature distinguishes three phases of digital transformation [Verhoef et al. 2021]: digitisation (focusing on transforming analogue information into a form of digital recording), digitization (i.e., using ICT to achieve business benefits by modifying the existing processes of the enterprise), and digital transformation (changing the current logic of the functioning of the business model, including creating added value through digital technology) [Kawalec 2021]. The generalizing first two stages are characterised by a gradual improvement in the way the organisation functions, while the last stage, digital transformation, is aimed at the overall modification and transformation of the enterprise, its supply chain, and business model [Parviainen 2017].

Another approach to digital transformation distinguishes four phases with different strategic goals and a different way to generate added value through the implementation of digital technologies [Subramaniam 2022]. The first stage is to improve operational efficiency by using real-time data to improve business processes. The second step is advanced operational performance based on data generated by customers (e.g., by installing sensors in products that transmit information about how they are used). The third phase covers data generated in the value chain as part of the services provided (an example is engine-mounted sensors that reduce fuel consumption in customers' vehicles, with some of those savings being captured by the manufacturer) [Kawalec 2021]. The fourth phase includes services based on the use of data from digital platforms, thanks to which it is possible to create consumption ecosystems. This, in turn, puts the company in a new role as the entity that creates the technological infrastructure for the development of the supply chain and, in a broader sense, for the entire business ecosystem. Subsequently, it is also necessary to manage the resulting value in such a way as to ensure mutual benefits for the actors involved in the digital supply chain.

In operational perspective transformation of DSC is a long term process that must be embedded in each of the resulting documents such as vision of a whole company, corporate strategy, digital corporate strategy and strategy for development of a supply chain [Preindl et al. 2020 p. 31]. On the basis of the formulated goals and assumptions, you can proceed to the assessment of the current state of supply chain covering such dimensions like: hardware, software, people, processes, and data. As a result several-year road map should be established with pilots and rollouts based on an optimal and most beneficial investments in a technology. It is highly recommended to start from a local pilot and along with confirmation of effectiveness and achievement of the presumed goal, it can be extended in a broader scope of supply chain. To accomplish of this step it is necessary to build strategic partnerships along the DSC [Preindl et al. 2020]. The whole transformation process should be finalised by cyclic revisions and evaluation of a whole system.

Therefore, it is assumed that the goal of the DSC transformation is to change the way digital technologies are used to create new business value for customers and improve performance of the organisation [Ageron et al. 2020]. The above attempts to define the meaning and essence of digital transformation indicate that the acquisition and implementation of modern technologies is not an end in itself, but a means to ensure the achievement of the overarching goal of creating value for the customer and its capture by business. Undoubtedly, harnessing technological opportunities to innovate in DSC requires a longer time horizon, partly because this process is more contextual and dependent on many variables than the implementation of the technology itself.

DATA AND RESEARCH SAMPLE

A total of 278 responses from Polish companies were selected at random. Of this group, 235 entities transformed towards business model innovation and therefore were included for further analysis. The structure of the surveyed entities (employment, ownership, and period of operation) is presented in Table 1. The most numerous in the sample are: large companies (41.2%), in terms of activity scope there is transport and warehouse management (33.6%), in case of time of operation are companies functioning more than 20 years and in terms of ownership dominates national owned companies (42.1%).

The quantitative research presented in the article was based on a questionnaire that contained 22 questions. Data were collected using the CAWI (Computer-Assisted Web Interview) method. A five-point scale was used to evaluate responses, where 1 – is not important and 5 – is very important. The research covers the period 2021-2022. The respondents to the study were employees of companies, especially middle-level managers dealing with innovation and strategic management, and specialists in this field. The collected data was coded and analysed. The Pearson correlation coefficient as well as factor analysis were used for the calculations with the use of MiniTab statistical software.

Table 1. Characteristics of the research sample, n=235

Employment size	1-9 employees – 12.8%	10-49 employees – 22.6%	50-249 employees – 23.4%	250 employees and more – 41.2%
Dominant scope of activity	Transport and warehouse management – 33.6%	Industrial processing – 15.7%	Other service activities - 11.4%	Wholesale and retail trade – 11.1%
Period of operation	1-3 years– 15.7%	4-9 years – 17.5%	10-19 years – 25.5%	20 years and more – 41.3%
Company's ownership	National – 42.1%	International under foreign control – 35.3%	International under Polish control – 22.6%	

Source: Self-developed materials.

RESEARCH RESULTS

The first of the aspects analysed is the degree of transformation process of the supply chain (Table 2). Altogether, there are 11 different steps of this process, which in general are implemented with rather a similar and moderate degree of intensity (average of a whole process is 3.61 in a scale from 1 to 5, where 1 is a minimal level of digital transformation and 5 is maximum level). In general, a higher degree of the implantation of DSC transformation process was observed for the building competences and the modelling phase (3.69) that indicate concentration on the operational aspect of the whole process. The most completed of all the activities of the process is training and developing skills (3.83) and the least implemented are tests and simulations of changes related to the transformation of DSC (3.41). But still the gap between them is not very significant.

Therefore, the next analysis that can give some spotlight is correlation between individual activities of the DSC transformation process (see Table 3). All of the activities examined in the DSC transformation process are shown to be positive correlated and those relationships are statistically significant.

Table 2. Implementation of the supply chain digital transformation process of companies, n=235

Process phase	Mean of the phase	Activities of digital transformation of the supply chain	Result	Standard deviation
Planning and preparation for the change	3.590	Initiating activities related to the digital transformation of the supply chain.	3.47	1.03
		Planning and integration of procurement. production and distribution processes.	3.74	1.00
		Tests and simulations of changes related to the digital transformation of the supply chain.	3.41	1.08
		Change management and project management.	3.74	0.97
Buildi ng compet ences	3.690	Training. Developing competences.	3.83	1.02
		Development of a digital supply chain operational model. Integration of inputs. transformation processes into outputs.	3.55	1.01
Implemen tation	3.593	Introducing new technologies in the enterprise.	3.68	0.98
		Integration of technologies existing in the enterprise.	3.58	0.98
		Integration of the company's technology with the technology of entities in the supply chain.	3.52	1.00
Evalua tion and impro	3.585	Development of a measurement system: measures and indicators as well as expected values. Control process.	3.68	1.00
		Scale and improve solutions for digital transformation of the supply chain	3.49	1.02

Source: Self-developed materials.

There is a moderate strong correlation between introducing new technologies in the enterprise and integration of technologies within the enterprise (0.587), as well as with entities in the supply chain (0.526) and between both activities related to integration of technologies (0.556).

Another set of relations is between: scale and improve solutions for transformation of DSC and integration of technologies within enterprise (0.587) and entities of supply chain (0.571), and development of measurement system (0.508).

This can be interpreted that to achieve better performance of DSC there is not only a need to integrate company's technology and also to match with other entities' of supply chain technology base of other entities, but it is also very important to implement sufficient and comprehensive control system over the activities carried out and engaged assets.

The next main point of analysis concerns technologies used for the DSC transformation process (see Table 4.). The most important is synchronised scheduling (4.08) (in scale 1-5), flexible and dynamic order processing (4.07), and smart delivery (3.96). Less common solutions used in DSC transformation process are the most sophisticated and advanced technologies like Intelligent product factory and smart factory. However, all of the technologies used received above average note, that means they all are crucial for DSC transformation process. Moreover, some insight can be show by analysing correlation coefficient for the applied technologies (see Table 5).

Table 3. Correlation of activities of supply chain digital transformation process of companies, n=235

Process of supply chain digital transformation	1	2	3	4	5	6	7	8	9	10	11
1. Initiating activities related to the digital transformation of the supply chain.	-										
2. Planning and integration of procurement processes. Production and distribution.	0.456*	-									
3. Tests. simulations of changes related to the digital transformation of the supply chain.	0.333*	0.188 **	-								
4. Change management and project management.	0.204* *	0.294*	0.317*	-							
5. Training. Developing competences.	0.236*	0.266*	0.272*	0.409*	-						
6. Development of a digital supply chain operational model. Integration of inputs. Transformation processes into outputs.	0.442*	0.320*	0.411*	0.369*	0.324*	-					
7. Introducing new technologies in the enterprise.	0.273*	0.337*	0.340*	0.345*	0.335*	0.378*	-				
8. Integration of technologies existing in the enterprise.	0.337*	0.354*	0.283*	0.351*	0.338*	0.440*	0.587*	-			
9. Integration of the company's technology with the technology of entities in the supply chain.	0.498*	0.398*	0.422*	0.277*	0.319*	0.453*	0.526*	0.556*	-		
10. Development of a measurement system: measures and indicators as well as expected values. Control process.	0.277*	0.321*	0.245*	0.309*	0.308*	0.456*	0.352*	0.343*	0.485*	-	
11. Scale and improve solutions for digital transformation of the supply chain	0.373*	0.265*	0.328*	0.355*	0.389*	0.487*	0.378*	0.516*	0.571*	0.508 *	-

Note: *p-value<0.001;**p-value<0.05.

Source: Self-developed materials.

Table 4. Relevance of elements (technologies) of digital supply chains of companies, n=235

Elements of digital supply chains	Result	Standard deviation
Synchronized scheduling	4.08	0.93
Flexible and dynamic order processing	4.07	1.03
Smart delivery	3.96	1.05
Digital platform of information exchange	3.84	1.04
Digitization of customer and consumer experience	3.76	0.95
Digital development - Intelligent product factory	3.58	1.02
Smart factory	3.49	1.07

Source: Self-developed materials.

The analysis of the interdependencies between implemented technologies shows several observations. First, there is moderately strong correlation of intelligent product factory with smart factory (0.617) and smart delivery (0.507). The smart factory is related to smart delivery (0.532). Finally, the digital platform for information exchange is correlated with flexible and dynamic order processing (0.507).

Table 5. Correlation of individual elements (technologies) of digital supply chains, n=235

Elements of digital supply chains	1	2	3	4	5	6	7
1. Synchronized scheduling	-						
2. Digitization of customer and consumer experience	0.426*	-					
3. Smart factory	0.290*	0.393*	-				
4. Smart delivery	0.285*	0.359*	0.532*	-			
5. Digital development - Intelligent product factory	0.296*	0.350*	0.617*	0.507*	-		
6. Flexible and dynamic order processing	0.469*	0.450*	0.341*	0.490*	0.322*	-	
7. Digital platform of information exchange	0.337*	0.444*	0.391*	0.407*	0.439*	0.507*	-

Note: *p-value<0.001.

Source: Self-developed materials.

The next analysis issue is the performance result of the DSC transformation process of companies (see Table 6). All of the observe indicators (profit, sales, market share, ROI and achieving competitive advantage) improve after implementation of DSC. The most significant raise concerns ROI (18.13%), market share (12.92%) and profit (11.83%). However, in case of ROI there is also the highest standard deviation (2.51), which indicates significant dispersion of results around the mean and can disturb the final reading of the indicator.

Table 6. Digital transformation of supply chain and results of companies, n=235

Phase of implementation	Metrics	Profit	Sales	Market share	ROI (return on investment)	Competitive advantage
Before introducing digital transformation	Mean	3.72	3.70	3.56	3.31	3.51
	Standard deviation	0.98	0.97	1.00	0.94	1.01
After introducing digital transformation	Mean	4.16	4.02	4.02	3.91	3.98
	Standard deviation	0.88	0.92	0.85	2.51	0.90
Percentage change		11.83%	8.65%	12.92%	18.13%	13.39%

Source: Self-developed materials.

Another analysis covers correlation coefficients for elements of digital supply chains (see tab. 5) and performance metrics (see tab. 6). All the interactions of the acquired variables were found to be positively correlated and statistically significant (p-value<0.05). The highest correlation coefficient is for smart deliveries and competitive advantage (0.344), synchronised scheduling and sales (0.338), digitisation of customer and consumer experience and competitive advantage (0.335) and flexible and dynamic order processing and sales (0.334). However, to give some more insight a multidimensional analysis more specifically factor analysis was applied (see tab. 7).

Altogether, there were 12 variables that indicate the designation of 12 factors, of which five will be analysed in detail. These four first factors explain 75.3% of the total variance of the variables investigated. Factor 1 (second column in tab. 7) indicates that almost 40% of the analysed companies analysed can be called "comprehensive" digital supply chain transformation because they achieve high positive correlation of all elements of digital transformation and also high positive results of performance metrics.

Factor 2 can be called the "laggards" of digital supply chain transformation with 13.6% of the companies investigated. These businesses can ensure relatively good performance results, but still significantly lower than in factor 1, without investing in digital supply chain transformation. In other words, those companies have a negative correlation between applied digital technologies of supply chain and business performance.

Factor 3 can be called 'operational excellence' of digital supply chain transformation with more than 8% of companies focus on synchronised scheduling, flexible and dynamic order processing, and digital platform of information exchange that can accelerate sales but with very significant cost of other performance metrics such as: ROI and competitive advantage.

Factor 4 represents 6.2% of the companies surveyed and can be called "market conquerors" of digital supply chain transformation. Those businesses focus on synchronised scheduling, smart factory, and smart delivery with results in rise of market share and sales.

Factor 5 covers 5.6% of the variance and can be called "logistic excellence" of the transformation of the digital supply chain. These companies focus on smart delivery as well as flexible and dynamic order processing that results in rise of ROI and competitive advantage.

The graphical result of the factor analysis is presented in a figure below (figure 1) consisting of three elements: 1) the vertical axis represents the number of applied technologies, 2) the horizontal axis represents the scope of company performance improvements calculated as a sum of correlation coefficients, 3) the size of a circle represents % of variance.

DISCUSSION AND CONCLUSIONS

The purpose of this article is to examine and describe the determinants of digital transformation of Polish company supply chains. The presented research results enabled the formulation of the following conclusions and points for discussion with the literature on the subject:

1) The transformation process of the DSC of Polish companies is implemented with rather similar and moderate degree of intensity (the average of a whole process is 3.61 out of a 5 point scale). This observation can be supported by the high rate of applied digital technologies like synchronised scheduling (4.08) (in scale 1-5), flexible and dynamic order processing (4.07) with relatively lower results for intelligent product factory (3.58) and smart factory (3.49). That result shows that there is focus on the operational efficiency with supplication and use of digital data. Altogether, this indicates relatively initial phase (the first or second stage of supply chain digital transformation) according to M. Subramaniam concept [2022].

Table 7. Factor analysis for digital transformation of supply chain and results of companies – correlation coefficients, n=235

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9	Factor 10	Factor 11	Factor 12
1. Synchronized scheduling	0.632	-0.082	0.438	0.227	0.019	-0.417	-0.283	0.120	-0.178	0.202	-0.033	0.088
2. Digitization of customer experience	0.660	-0.165	0.167	-0.318	-0.421	-0.067	-0.060	-0.432	-0.048	-0.131	-0.131	0.003
3. Smart factory	0.619	-0.436	-0.306	0.208	-0.348	-0.047	0.106	0.053	-0.009	0.032	0.388	0.007
4. Smart delivery	0.589	-0.476	-0.112	0.161	0.344	-0.025	0.376	-0.250	0.035	0.136	-0.148	0.154
5. Intelligent product factory	0.610	-0.419	-0.423	0.123	-0.051	0.050	-0.199	0.278	-0.008	-0.162	-0.311	-0.111
6. Flexible and dynamic order processing	0.658	-0.239	0.481	-0.042	0.284	-0.021	0.112	0.087	0.100	-0.327	0.140	-0.196
7. Digital platform of information exchange	0.644	-0.239	0.238	-0.315	-0.007	0.492	-0.106	0.172	0.075	0.284	0.023	0.050
8. Profit	0.623	0.513	0.005	-0.029	-0.200	-0.184	0.326	0.133	0.201	0.208	-0.118	-0.228
9. Sales	0.640	0.530	0.118	0.195	-0.146	0.163	0.126	0.158	0.034	-0.234	-0.045	0.333
10. Market share	0.615	0.430	-0.043	0.357	0.099	0.326	-0.097	-0.253	-0.273	0.044	0.032	-0.199
11. ROI	0.604	0.259	-0.329	-0.479	0.218	-0.156	0.088	0.122	-0.354	-0.031	0.082	0.045
12. Competitive advantage	0.657	0.301	-0.298	-0.058	0.231	-0.119	-0.350	-0.176	0.387	0.006	0.107	0.055
Variance	4.7588	1.6282	1.0063	0.7381	0.6720	0.6312	0.5621	0.5334	0.4420	0.3924	0.3428	0.2927
% Variance	39.7%	13.6%	8.4%	6.2%	5.6%	5.3%	4.7%	4.4%	3.7%	3.3%	2.9%	2.4%

Source: Self-developed materials.

2) However, DSC transformation, even at this stage of implementation, gives positive results for all of the assessed measures (see Table 6.), i.e. profit, sales, market share, ROI and competitive advantage were improved after implantation of digital technology into supply chain. The greatest increase was noticed in terms of ROI (by 18%), which can be the result of better access and utilisation of digital data and adjustment and integration of the technological base within DSC.

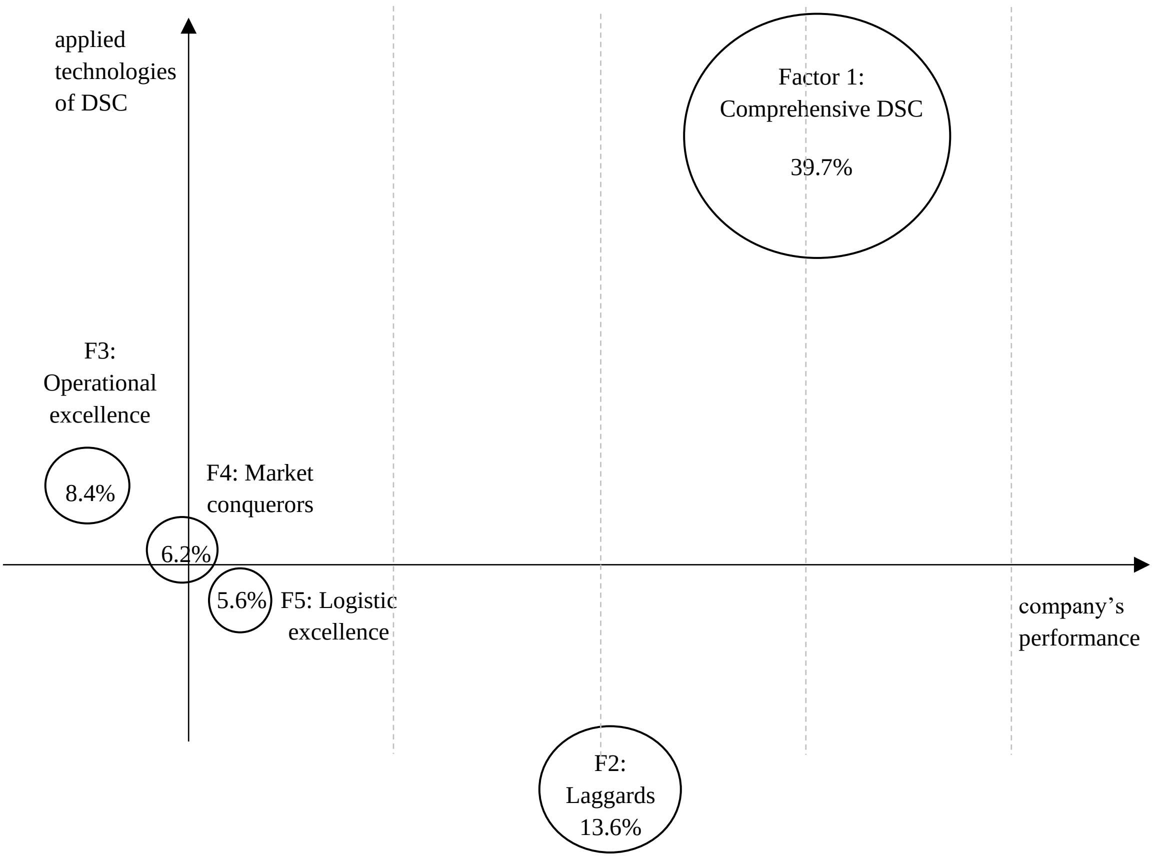

Fig. 1. Applied technologies of digital supply chain and company's performance – graphical presentation of factor analysis

Source: self-developed materials.

3) The factor analysis confirmed that the systematic and comprehensive approach to the DSC transformation process gives positive results for all performance metrics (Factor 1: 'Comprehensive DSC'). What is interesting is that skipping investment in DSC transformation (Factor 2: 'Laggards') gives better results than focusing only on a specific area of technology (ie, Factor 3: "Operational excellence" or Factor 4: 'Market conquerors').

4) In terms of practical implications considering applications for implementation projects, there is relatively strong correlation between introducing new technology and its integration, both within company and other entities of supply chain. This relation, which is also conditions Scaling and improving of supply chain digital transformation. However, to achieve technology integration, the company must mitigate "difficulty of visualizing the digital and physical flows and the determination of the appropriate level of interconnectivity between the physical and digital world" [Garay-Rondereo et al. 2020].

5) In summary, DSC transformation should be treated as a strategic renewal project and therefore need to be embedded in a broader strategic context, by concluding its assumptions within a vision of a whole company, corporate

strategy, digital corporate strategy and strategy for development of a supply chain [Preindl et al. 2020]. To provide broader context and help in the digital transformation process company can use the innovation concept of the business model [Wang et al. 2018]. By applying of this framework, it is possible to analyse the interdependencies between the resources, activities, and needs of the involved entities and the financial result achieved.

LIMITATIONS OF RESEARCH

The presented research procedure is not free from some limitations. The first is the size of the surveyed sample, which could be expanded in the future, including foreign entities and specific division between types of company activities (i.e. industries, services, mining and energy production, agriculture, and so on) and type of production model (Make-to-stock, Make-to-order, Assemble-to-order, Engineer-to-order) [Cyplik, Zwolak, 2022 p. 162].

The second limitation are performance metrics applied in the research, while proposed to use a more complex measurement system combined of real-time control on strategic, tactical and operational level based on engaged technology like IoT, Big Data, blockcahin technology, online communication channels [Ageron et al. 2020 p. 135, Bal, Pawlicka 2021 p. 73]. This could help to close the gap between the existing theoretical approach and the real needs of companies in terms of the control of DSC transformation process.

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ORIGINAL PAPER

APPLICATION OF INDUSTRIAL INTERNET OF THINGS (IIOT) IN THE PACKAGING INDUSTRY IN POLAND

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ABSTRACT. Background: This paper explains the concept of the Industrial Internet of Things (IIoT) and highlights the benefits of its adoption. The purpose of the study was to identify and evaluate practices and approaches of organisations toward the implementation of IIoT solutions in the packaging industry in Poland.

Methods: The results are based on non-sensitive quantitative data collected with the use of a survey questionnaire method and CATI (Computer Assisted Telephone Interview) as a data collection technique. Participants completed anonymous survey questionnaires, with responses analysed collectively without the identification of individuals. No continuous tracking or observation methods were used, and the data did not include personal information such as health, genetics, beliefs, or political views.

Results: The results reveal that companies within this industry are not early adopters of IIoT, but they are rather digitally immature, with a poor degree of IIoT implementation, poor degree of quality systems digitisation, and no plan towards transformation to enterprise systems such as MRP, ERP, or CRM. The application of IIoT has potential for improvement. The paper outlines the analysis of organisational culture in terms of supporting innovation and continuous improvement, showing that the level of support is moderate, however, the bigger company is, the more supporting the organisational culture it has.

Conclusions: Data reveal that the application of IIoT solutions in the packaging industry in Poland is still not very common. Poor adoption of IIoT may be related to fear of technology, budgetary issues, or lack of qualified staff. Although digitisation already changed the software and the hardware side of organisations, most of them are not digitally mature enough to be able to take advantage of the fourth industrial revolution, which can be a strategic advantage for early adopters.

Key Words: Industrial Internet of Things (IIoT), Radio-frequency identification (RFID), sensors, packaging industry, quality control

INTRODUCTION

The Internet of Things (IoT) is one of the key technologies of the fourth industrial revolution (Industry 4.0), which is focused on real-time data monitoring [Almada-Lobo, 2016; Vaidya, Ambad, Bhosle, 2018]. IoT consists of various multiple devices with embedded systems that are connected to the telecommunication network, the Internet, and have the ability to generate and automatically send information without direct human intervention [Wójcicki et al., 2022]. Connecting devices to the Internet has started a new era of data analysis, automation, and opportunities for innovation. IoT is being widely implemented in many areas of our life, including healthcare, agriculture, manufacturing, quality control, transport and logistics, and energy, and has already passed the stage of being seen only as an exploratory technology [Deloitte, 2021]. The use of IoT is on an ascending curve, with predictions that by 2030 more than 500 billion devices will be connected to the Internet [Cisco, 2021].

Industry 4.0 and digital transformation change the world and societies into modern and super-smart, where everything is readily available at hand. To catch up with the growing trend, industries must invest in IoT technologies [Zikria et al., 2021)]. The application of IoT in the industry is called the Industrial Internet of Things (IIoT). IIoT is an extension of IoT, providing industries with tools to create a

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competitive advantage. As IIoT serves the industry, it has to meet requirements higher than IoT which serves the consumer domain. IIoT leads to the creation of Smart Factories where objects such as machinery, devices, and products are equipped with sensors that are connected to each other and to the Internet [Gebremichael et al., 2020]. Data collection, analysis, and exchange enable machine-to-machine learning (M2M) and changing modes and settings without the need for human intervention. The IIoT uses sensors and actuators to a great extent, for example, position sensors, motion sensors, biosensors, mass or volume sensors,, measurement sensors and environment sensors [Alexopoulos et al., 2018]. Different authors point to different advantages of the IIoT application, including access to real-time online data that enhance decision making, improve performance, productivity, efficiency, and quality [Fatorachian and Kazemi, 2021]; tracking the status and positions of raw materials, work-in-progress, and final products [Almada-Lobo, 2016]; controlling production processes [Vaidya, Ambad, Bhosle, 2018]; reducing human errors [Rejeb and Keogh, 2019]; reducing equipment maintenance time and costs [Peng et al., 2021]; reducing manufacturing costs through optimised assets and inventory management; reducing machine downtime; controlling the workplace environment [Garg et. al., 2022]. Incorporating IIoT solutions in organisations allows for moving from a reactive approach to a proactive approach in areas such as maintenance of equipment and tooling, quality, inventory management, and operations. Additionally, a better understanding of the processes can contribute to efficient and sustainable manufacturing by minimising scraps, losses, and wastes.

One of the IIoT solutions is Radio Frequency Identification (RFID). RFID aims at automatic object identification via radio waves, where a tag transmits its identity to the tag reader [Wójcicki et al., 2022]. The tag can be either attached to a product or embedded e.g. within the device or machine. The tag is a carrier of a unique code that contains information. When an item (e.g. product, device, packaging) equipped with an RFID tag moves through the tag reader (e.g. installed on the warehouse gate or racks), data are collected, grouped, and send to a database [Grimaldi et al., 2020], which can be connected to software such Manufacturing Resource Planning (MRP), Enterprise Resource Planning (ERP), or Warehouse Management System [Arulogun, Falohun, Akande, 2016; Liukkonen, 2015]. RFID can be applied in various areas, including [Liukkonen, 2015]: warehouse and inventory management; tool management; supply chain management; process monitoring, management and control; life cycle management. The application of RFID enhances transparency within the supply chain; facilitates inventory management; helps detect variations in production [Rejeb and Keogh, 2019)]; improves traceability; and prevent counterfeiting.

Packing is one of the operations that take place in most of the production process [Wolniak and Zadura, 2012)]. Packaging products can be made of various material types, such as paper, plastic, metal, or glass. Packaging has many functions, such as [Sykut, Kowalik and Droździel, 2013]: protecting the product during storage, transportation and use; facilitating production, wholesale and retail; informing consumers, for example, on the product composition or shelf life, and marketing. Packaging provides protection from chemical, biological, and physical threats [Marsh and Bugusu, 2007], can influence the shelf life of the product, and maintain or increase the quality and safety of packaged products. Packaging is an important part of most products and is still subject to innovation.

The purpose of this paper is the identification and evaluation of the practices and approaches towards the implementation of IIoT solutions in the packaging industry in Poland. The paper presents an outline of the status of the digitisation of production and quality assurance systems; the application of IIoT in a production environment; and the utilisation of wireless communication to enhance traceability.

MATERIALS AND METHODS

The study has been conducted in 2021. Research has been divided into two major parts: the theoretical part, and the empirical part as shown in Figure 1. The results of the theoretical part have been published in the article titled *Internet of Things in Industry: Research Profiling, Application, Challenges and*

Opportunities [Wójcicki et al., 2022]. The main study was conducted with the application of a triangulation strategy. The triangulation strategy consists in combining various methods while examining one research problem, aiming to increase the amount of knowledge collected and the value of the data. The data was collected using a combination of three methods: Computer Assisted Web Interview (CATI), Individual In-depth Interview (IDI), and Case Study.

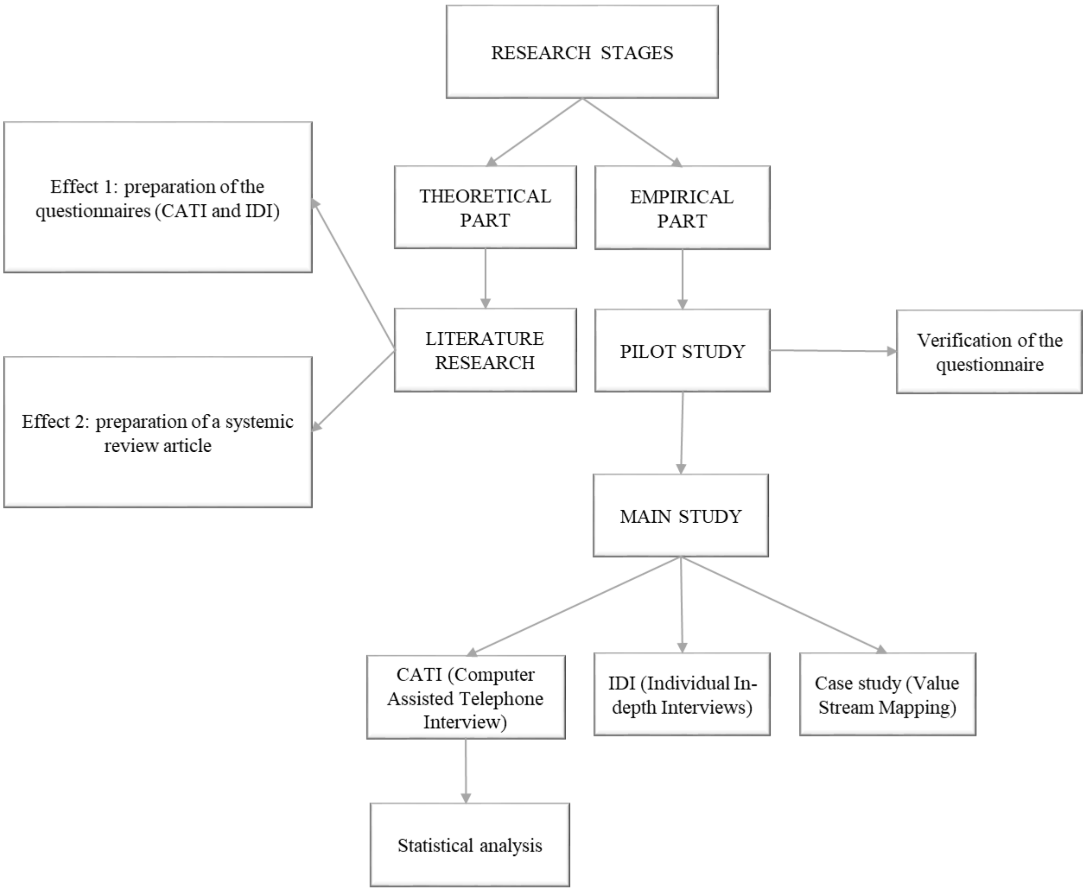

Fig. 1. Research plan

During the first stage of the main study, quantitative data have been collected using a survey questionnaire and the CATI (Computer Assisted Telephone Interview) method as a technique of data collection. The research population consisted of 132 companies located in Poland in the Greater Poland Voivodeship and classified under the following classification codes:

17.21.Z manufacture of corrugated and corrugated cardboard as well as paper and cardboard packaging;

22.22.Z Production of plastic packaging.

68 companies participated in the study, which constitutes 51% of the surveyed population. The structure of the sample based on the product, the size of the company, and the origin of the capital is presented in Figures 2-6. Based on the sample structure, most of the researched companies were in the SMEs (98.5%) with solely or the majority of polish capital (94.1%). More than half of the companies surveyed declared production of packaging intended to have direct or indirect contact with food (51.5%) and realisation of printing on packaging (58.8%). 44.1% of companies specialise in plastic packaging, 38.2% of companies in paper packaging, and 17.6% produce packaging from different packaging materials.

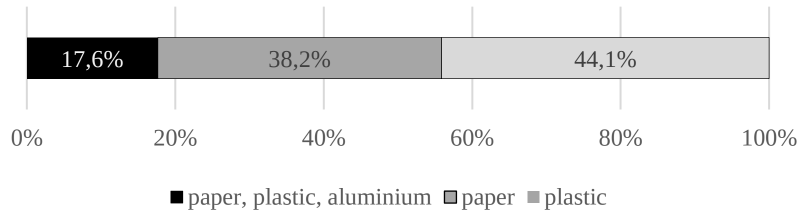

Fig. 2. Structure of a sample based on produced packaging material

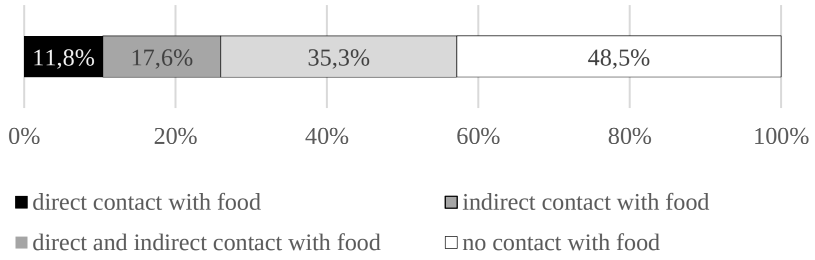

Fig. 3. Structure of a sample based on the packaging purpose

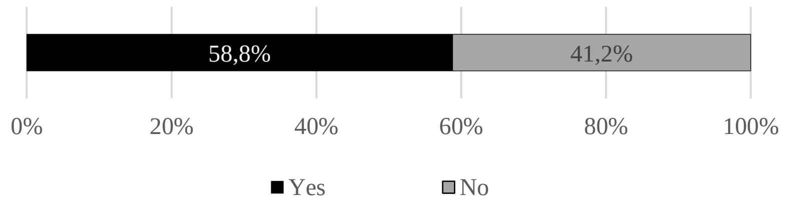

Fig. 4. Structure of a sample based on the realisation of printing processes on packaging

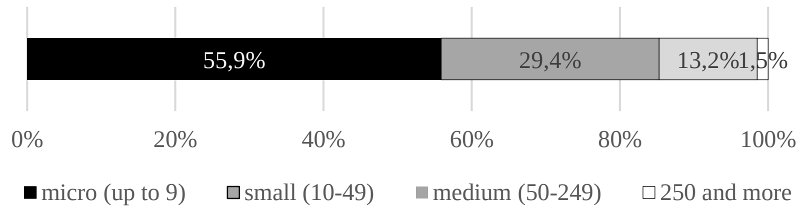

Fig. 5. Structure of a sample based on the number of employees

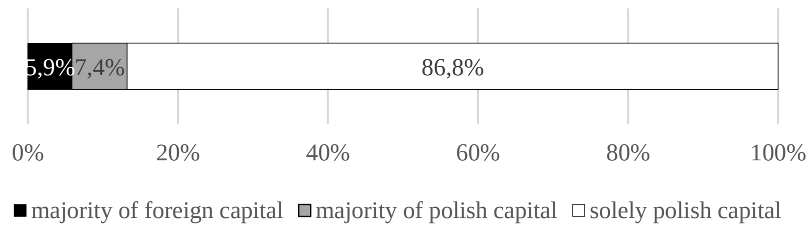

Fig. 6. Structure of a sample based on the origin of the capital

Telephone interviews were conducted only with employees at selected positions within the organisations that are competent to provide information on the subject matter (company owners, quality directors or managers production directors or managers, and technologists) as presented in Figure 7. The questionnaire contained 17 questions related to quality control methods and techniques, the use of optical sensors, the application of systems, and IIoT.

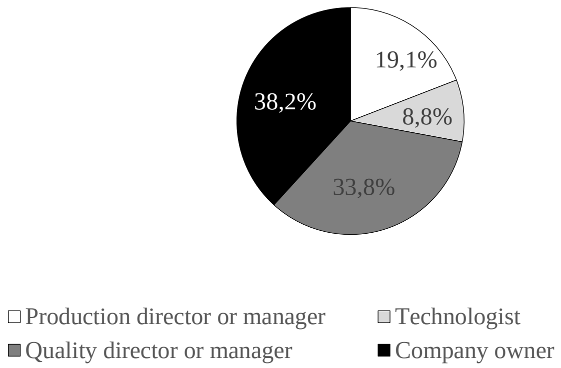

Fig. 7. Respondents structure

Most of surveyed companies have implemented a quality management system according to ISO 9001 (88.1%). Only 21.4% of companies have implemented environmental management systems according to ISO 14001 or EMAS, and only 11.9% of companies implemented the BRC Packaging Materials standard.

The second stage of the main study was conducted using IDI (Individual In-Depth Interviews) with representatives of three companies. IDI data acquisition methodology is a discussion-orientated form of qualitative research. The questions are open-ended, which does not allow the respondent to answer just in one word. Interviews were conducted with company representatives – employees selected based on their knowledge, experience, and position in organisations. The third stage of the main study contained the preparation of a value stream map based on a case study.

This paper aims to review and evaluate the application of Industrial Internet of Things (IIoT) solutions in the packaging industry in Poland. Data presented in the results and discussion chapter are prepared based on qualitative research – CATI (first stage). The collected data are not sensitive, do not concern health, genetic information, intimate life, political views, ethnicity, beliefs, and religious beliefs and the study did not involve methods of continuous tracking or observation of participants. Participants were involved in completing survey questionnaires (anonymous responses analysed collectively without the identification of individual respondents).

RESULTS AND DISCUSSION

Digitisation of production systems

The first question concerned recording data during quality control processes, including verification of raw materials quality during delivery and incoming inspection processes, verification of product quality during the production process, and verification of product quality at the end of the production process, during the product release stage. As shown in Figure 8. 77.3% of the companies surveyed still use a manual recording of the quality inspection results, and 30.6% do not even analyse those results. Only 22.8% of the organisations surveyed use electronic records, but only 2.8% are connected to the IT system. Many organisations use a manual recording of quality inspection results but fail to analyse them. In many cases, this can be due to a lack of resources or expertise.

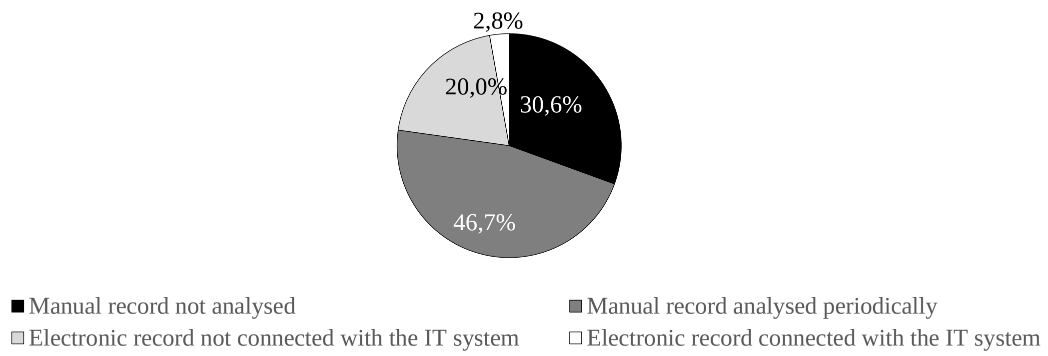

Fig. 8. Types of records in quality control processes

Those companies where records are coupled with the IT system also declared that they have implemented dedicated software for creating processes and managing Quality Management System (QMS) documentation (e.g., Adonis, Qualio, MasterControl, Q-Pulse, Pando, or other) and dedicated software enabling digital operating instructions (e.g., Visual Factory, VKS, Aegis Paperless Shopfloor, or other). Most of surveyed companies do not use such dedicated software and do not plan to implement it in the near future (Figure 9).

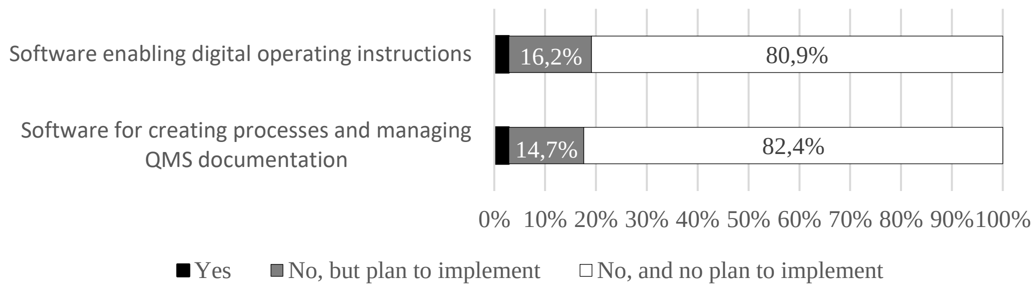

Fig. 9. Use of dedicated software for QMS and paperless Shopfloor

Although only 2.9% of companies use dedicated QMS software for documentation management, most of them (79.4%) do provide electronic documents on workstations. In these companies, workstations are equipped with screens, monitors, or mobile interfaces; however, only 13.2% implemented paperless shop floor (Figure 10). The paperless factory aims to eliminate paper-based processes and digitise the entire manufacturing process. In a paperless shopfloor, all information related to production, such as work orders, instructions, and quality control data, would be stored and accessed electronically. Eliminating paper-based processes can improve communication and collaboration between departments, reduce errors, increase productivity, save time, and improve product quality.

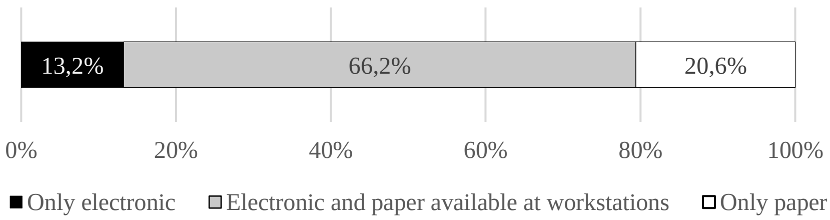

Fig. 10. Use of electronic documentation at work stations

Digitisation of a production system requires the implementation of some enterprise systems. The largest percentage of companies declared the implementation of Material Requirements Planning (23.5%), Enterprise Resource Planning (19.1%), and Customer Relationship Management (16.2%). Warehouse Management Systems and Supply Chain Management were the least popular, with only 11.8% of the implementation (Figure 11).

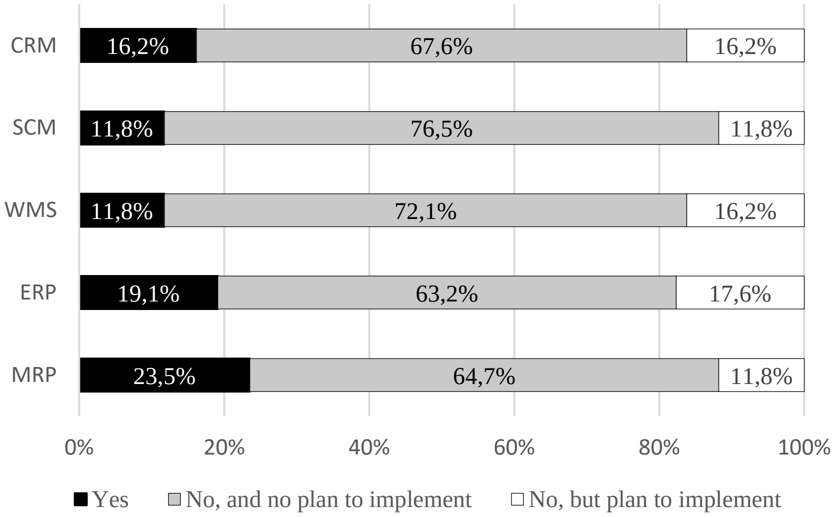

Fig. 11. Application of enterprise systems

The authors examined company relationship between the size and the implementation of MRP, ERP, WSM, SCM, and CRM systems. Due to the fact that only 9 companies employing 50-249 people and 1 company employing 250 or more people took part in the survey, the size of companies was divided into two categories: up to 9 employees and above 10 employees. Therefore, the last category included companies that employ at least 10 people, including companies employing 10-49 people, 50-249 people and 250 and more people. The same approach was applied to all other tests examining the influence of company size on different factors. On the other hand, with regard to whether the company has an appropriate system implemented, two categories were distinguished: 'yes' and "no". The second of these categories included companies that do not have an implemented system and do not plan to implement it, and those that do not have it but plan to do so in the future. Such a procedure was necessary to be able to apply the chi-square test of independence. The p-value analysis (Table 1) reveals that there are no significant dependencies between the size of the company and whether the company has an appropriate system implemented or not (regardless of the type of system). In each case, the p-value was higher than the commonly accepted significance level of 0.05. It can be concluded that regardless of the size of the company, the vast majority of companies do not have an appropriate system implemented.

Table 1. Size of the company vs. implemented enterprise systems

		Yes	**No**	**p-value**
	> 10	26.7%	73.3%	
ERP	< 9	13.2%	86.8%	p=0.160
	> 10	26.7%	73.3%	
WMS	< 9	7.9%	92.1%	p=0.265
	> 10	16.7%	83.3%	
SMC	< 9	10.5%	89.5%	p=0.721
	> 10	13.3%	86.7%	
CRM	< 9	13.2%	86.8%	p=0.447
	> 10	20.0%	80.0%	

It can be observed that even if a company has more than one system implemented, they are not always connected with each other to share or exchange information (Figure 12).

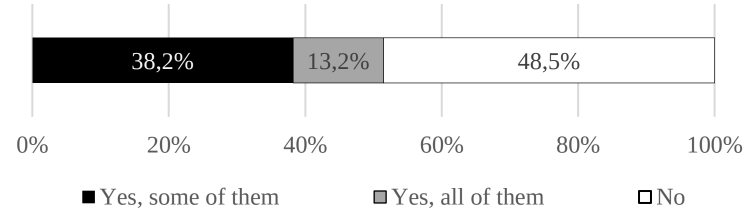

Fig. 12. Integration of IT systems (exchange and share information between systems)

Most companies store records on a central server in the company (75.0%) and only 5.9% store data on a server outside the company (Figure 13). We examined whether the size of the company or the origin of the capital influences the place where the data is stored. The size of the company, similar to the previous analysis was divided into two categories. Regarding where the collected data from IT systems is stored, only two categories were considered: on workstations and on a server in the company (centrally). Due to the fact that only 4 companies declared that the data collected from IT systems is stored in the cloud, answers from this category were excluded from the correlation analysis. P-value analysis shows that there is no statistically significant relationship between company size and whether the collected data from IT systems is stored on workstations or centrally on the company's servers (Table 2). This is due to the fact that in each case the calculated p-value is higher than the commonly established significance level of 0.05. Cloud computing technologies provide borderless sharing and access to information [Esmaeilian et al., 2020], however, it can be noticed that, regardless of the size of the company, the vast majority of data collected from IT systems is not stored in Cloud, but centrally on a server in the company. This is in line with the data in [Szozda, 2017], where it was indicated that companies in the US, Germany, and Japan are not eager to store their data on external servers (outside the country) (19, 14 and 12%, respectively).

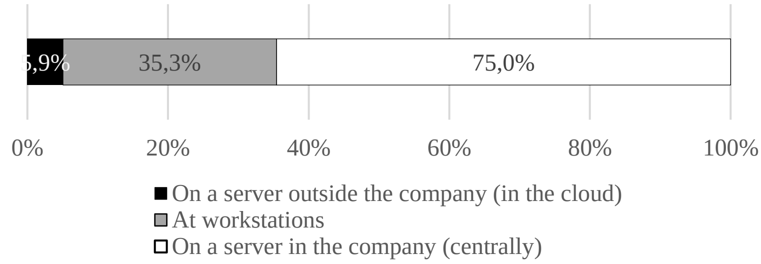

Fig. 13. Place of storing data from IT system

Table 2. Size of the company vs. place of data storage

		Yes	No	p-value
At workstations	< 9	31.6%	68.4%	p=0.471
	> 10	40.0%	60.0%	
On a central server	< 9	76.3%	23.7%	p=0.778
	> 10	73.3%	26.7%	

The origin of the capital data was divided into two categories: enterprises with only Polish capital and others. Such a procedure was necessary in order to be able to apply the chi-square test of independence, and it was applied for all other tests examining the correlation between the origin of the capital and other factors. Regarding where the collected data from IT systems is stored, similarly, as in the above analysis, two categories were considered: on workstations and on a server in the company (centrally). The p-value analysis shows that there is no statistically significant relationship between the origin of capital and whether the data collected from IT systems is stored on workstations or centrally on servers in the company. This is due to the fact that in each case the p-value was higher than the commonly established significance level of 0.05. Regardless of the the origin of capital, the vast majority of companies store data centrally on a server in the company (Table 3).

Table 3. Origin of the capital vs. place of data storage

		Yes	No	p-value
At workstations	Polish	39.0%	61.0%	p=0.103
	others	11.1%	88.9%	
On a central server	Polish	72.9%	27.1%	p=0.302
	others	88.9%	11.1%	

It can be concluded that the digitization level of the companies surveyed is low. According to other research studies [Szopa & Cyplik, 2020], SMEs show a rather low level of digitisation. This suggests that Polish companies are not yet ready for digital transformation. It can also be noted that the bigger the company, the higher the digitisation level of the surveyed companies.

Internet of Things in a production environment

36.8% of the companies declared that their production environment is connected to the Internet, 35.3% declared the usage of optical sensors, but only 23.5% of the companies use sensors that are connected over the Internet to devices (Figure 14). We examined whether there is a correlation between the size of the company and the connection of the production environment to the Internet or the use of optical sensors. Regarding whether the company's production environment is connected to the Internet and whether the company uses optical sensors, two categories were taken into account: ‘yes' and “no”. The p-value analysis performed for the chi-square test of independence reveals that there is no statistically significant correlation between the size of the company and whether the production environment in the company is connected to the Internet and between the size of the company and the use of optical sensors. The data presented in Table 4 confirm that there is no correlation between the size of the company and whether its production environment is connected to the Internet and whether they use optical sensors. It can be seen that, regardless of the size of the company, most of them do not use optical sensors, and the production environment is generally not connected to the Internet. Although the percentage of companies in the group of small and medium companies (+10 employees) is greater than in the group of micro companies, these differences are not statistically significant.

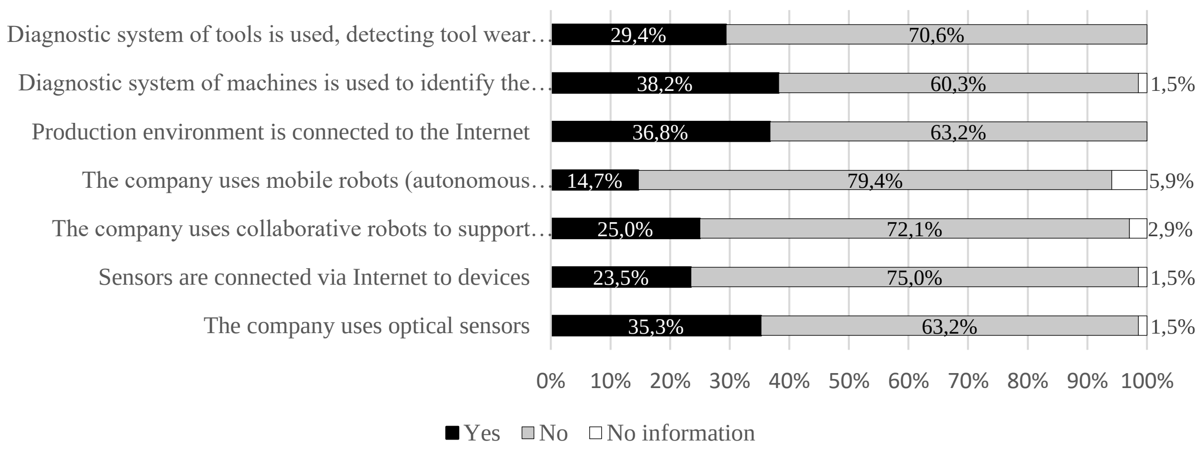

Fig. 14. Connection of work environment to the Internet

Table 4. The size of the company vs. connection of the production environment to the Internet or the use of optical sensors

		Yes	No	p-value
Connection to Internet	< 9	34.2%	65.8%	p=0.623
	> 10	40.0%	60.0%	
Use of sensors	< 9	28.9%	71.1%	p=0.179
	> 10	44.8%	55.2%	

Regarding the correlation between capital origin and the connection of the production environment to the Internet, the p-value analysis shows that there is no statistically significant correlation between factors examined. When analysing Table 5, it might seem that such a relationship exists. In the group of enterprises with only Polish capital, more than 66% do not have a production environment connected to the Internet. The opposite situation is observed in the group of other companies, among which over 55% declared that the production environment is connected to the Internet. However, the lack of dependence results from the fact that the majority of the companies in the sample had only Polish capital. In the group of other companies, there were only 9 enterprises, hence the chi-square test of independence did not reject the hypothesis of independence between the analysed features (the origin of capital vs. whether the production environment is connected to the Internet).

At the adopted significance level of 0.05, the hypothesis that there is no relationship between the origin of capital and whether the company uses optical sensors should be rejected in favour of the hypothesis that there is such a relationship (the calculated p-value was p=0.038 and is lower than the commonly established significance level of 0.05). Data presented in Table 5 confirm capital relationship between the origin and the usage of optical sensor use. In the group of enterprises with only Polish capital, the vast majority (69.0%) do not use optical sensors, while in the group of other enterprises (with foreign capital), the majority (66.7%) declared that such sensors are used. Wahab S. et al. [2021] pointed out that in the implementation of IoT in the Malaysian industry a significant role in supporting the process lies in external partners (through mergers and acquisitions).

Table 5. The capital origin vs. connection of the production environment to the Internet or the use of optical sensors

		Yes	No	p-value
Connection to Internet	Polish	33.9%	66.1%	p=0.209
	Other	55.6%	44.4%	
Use of sensors	Polish	31.0%	69.0%	p=0.038
	other	66.7%	33.3%	

Sensors connected via the Internet to production devices allow parameters of production to be changed with human intervention (23.5%) or without human intervention (19.1%).

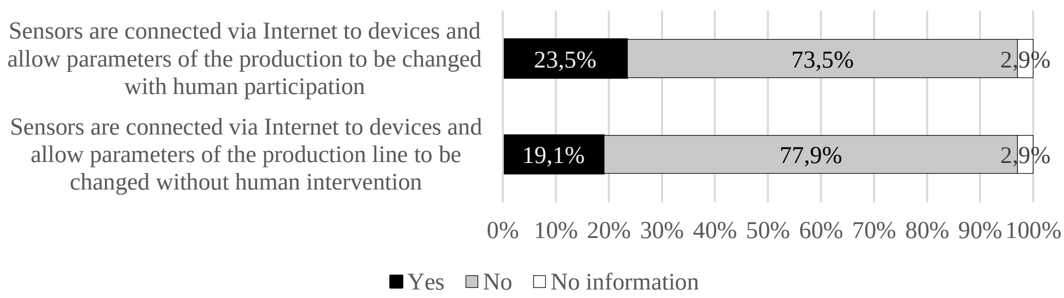

Fig. 15. IoT enabling production parameters to be changed with / without human intervention

Wireless communication ensuring traceability

RFID tags are used to ensure traceability in 22.1% of companies. These companies use wireless communication to identify and locating products at all stages of production, from raw materials, through semi-finished products (work-in-progress), to finished products (Figure 16).

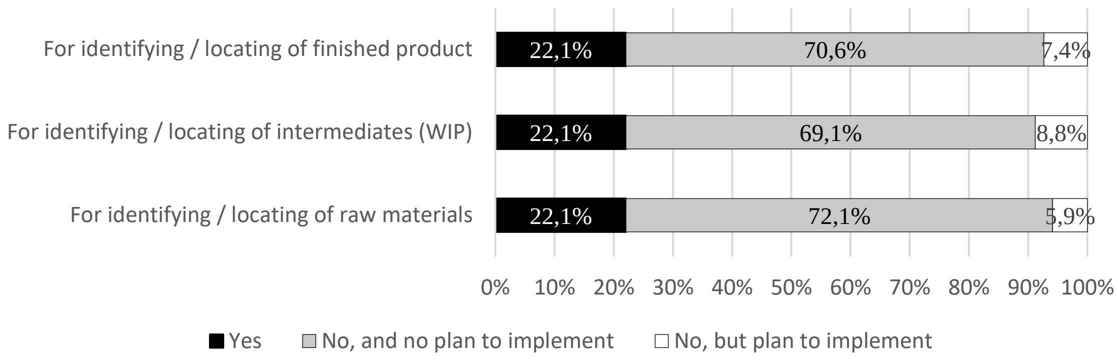

Fig. 16. Application of data carriers (e.g. RFID tags) to ensure traceability

RFID has been widely implemented in industries where machines monitor and control the speed and statuses of assembly parts, such as automotive, car parts, machine, heavy industry, electronic, food industry, and pharmaceutical industries [Liukkonen, 2015; Masniak et al., 2019]. Although the RFID solution is well known and is low cost, it is not used on a large scale in the packaging industry in Poland.

We examined the correlation between the size of the company and the use of RFID. Regarding whether the company uses RFID data carriers to ensure traceability, two categories were distinguished: "yes" and "no". The second of these categories included companies that do not use them and do not plan to do so and those that do not use them but plan to do so in the future. Such a procedure was necessary to be able to apply the chi-square test of independence. When performing the p-value analysis, it can be noticed that there is no statistically significant relationship between the size of the company and whether the company uses data carriers to ensure traceability (regardless of whether it concerns raw materials, semi-finished products or finished products). In each case, the p-value took values higher than the commonly established significance level of 0.05. This is confirmed by the data in Table 6. It can be seen that, regardless of the size of the company, the vast majority of them do not use data carriers to ensure traceability.

Table 6. The size of the company vs. the use of data carriers such as RFID

		Yes	No	p-value
Raw materials	< 9	15.8%	84.2%	p=0,161
	> 10	30.0%	70.0%	
WIP	< 9	21.1%	78.9%	p=0,822
	> 10	23.3%	76.7%	
Finished products	< 9	18.4%	81.6%	p=0,416
	> 10	26.7%	73.3%	

Respondents have been asked to assess their organisational culture in terms of supporting innovation and continuous improvement on a 5-point Likert scale, where: 1 – strongly disagree, 2 – rather disagree, 3 – neither agree, nor disagree, 4 – rather agree, 5 – strongly agree. The average value of all factors for all organisations was a=3.34. The mean and standard deviation for individual factors are presented in Figure 17. After the analysis of data differentiated by company size, it appears that the bigger the company, the more supportive the organisational culture in terms of innovation and improvement it has. Although the differences are not significant, a slight improvement can be noticed. The average for micro-companies with up to 9 employees was a=3.29, for small companies, between 10, and 49 employees a=3.34, and for medium-sized and large companies, with a number of employees above 50, the average was a=3.49.

Fig. 17. Organisational culture supporting innovation and improvement

The results are similar to findings on change readiness [Batz et al., 2018; Hizam-Hanafiah et al., 2021], which demonstrate that although there are tools allowing for technology readiness (digitization, IoT, Industry 4.0), an even greater impact on companies transformation towards Industry 4.0 has organisational change readiness. Although there is technology that allows this change, the organisations surveyed are not ready for that change. It may be assumed that the reasons for this are among others fear of change of individual employees, management, and the entire organisation. These barriers are interrelated and can have a compounding effect on each other. Overcoming these barriers requires a holistic approach that addresses both the technical and nontechnical aspects of IIoT implementation, and involves collaboration across different functions and stakeholders within the organisation.

CONCLUSION

The manual recording of quality inspection results is common practice in the majority of companies surveyed (77.3%). 1/3 of those surveyed do not analyse the results of inspections. These results are surprising due to the fact that 88.1% of the sample declared the implementation of the ISO 9001 system, in which much emphasis is placed on performance evaluation, including monitoring, measurement, analysis, and evaluation [ISO 9001:2015]. Only 22.8% of organisations use electronic records and a negligible percentage of respondents declared that the electronic record is connected to the IT system. Facing the fourth industrial revolution, it is alarming that this form of recording is still not common. Furthermore, a marginal percentage of respondents implemented dedicated digital QMS software or entirely paperless Shopfloor. The MRP system has been implemented by 23.5%, ERP by 19.1% and CRM by 16.2%. and there are no significant dependencies between the size of the company and whether the company has any system implemented or not. Systems connectivity still seems to be an issue, as 48.5% of the respondents did not connect their systems with each other to share or exchange information within the company.

The conducted research showed marginal use of optical sensors in the analysis group of companies. Regardless of the size of the company, most of them do not use optical sensors, and their production environment is generally not connected to the Internet. Similarly, regardless of the size of the company, RFID tags are used to ensure traceability only in 22.1% of those surveyed. Those companies use wireless communication for identifying and locating products at all stages of production, from raw materials, through semifinished products (work-in-progress), and finished products. However, there is a relationship between the origin of capital and whether the company uses optical sensors. In the group of companies with only Polish capital, the vast majority do not use optical sensors, whereas, in the group of companies with foreign capital, the majority declared that such sensors are used. It can be concluded that the usage of optical sensors and the application of RFID have potential for improvement for companies operating in the packaging industry, in particular those with entirely Polish capital.

The analysis of an organisational culture in terms of supporting innovation and continuous improvement shows that the larger company is, the more supporting organisational culture it has in terms of innovation and improvement. Although the differences are not significant and the general level of support culture is moderate, a slight difference can be noticed.

Data reveal that the application of IIoT solutions in the packaging industry in Poland is still not very common. It can be assumed that surveyed companies are in the aspiration phase when it comes to the implementation of Smart Factory [Odważny et al.; 2018]. This may be related to a technology fear, but also to budgetary and staff qualification issues. According to Microsoft's IoT Signals Report [Microsoft, 2021], 26% of organisations reported that lack of budget and staff was one of the reasons for holding off on IoT adoption. Companies have problems employing adequately skilled and experienced employees to drive digital transformation projects. Also, an organisational culture that does not support innovation may be a factor influencing the inhibition of changes. Digitisation has already changed the software and the hardware side of organisations, however, as data shows, not all of them are digitally mature enough to be able to take advantage of the fourth industrial revolution [Pegn et al., 2021, Rejeb,, Keogh & Treiblmaier, 2019], which can be a strategic advantage for early adopters. Furthermore, most of the actions taken are rather spontaneous rather than systematic [Ministerstwo Przedsiębiorczości i Technologii; 2019].

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ORIGINAL PAPER

OPTIMAL DECISION MAKING FOR EMPTY CONTAINER MANAGEMENT AT SEAPORT YARD

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ABSTRACT. Background: In global trade, shipping companies are forced to manage empty containers due to imbalances in international trade activities. For decision-makers, the problems require considering restrictions and an uncertain environment and repositioning or leasing the containers to satisfy the rapidly changing global demands regardless of the epidemic outbreak's impact on the seaport. The proposed approach can help decision-makers manage the empty container in port yards more effectively under market uncertainty by employing the Bellman optimality principle for the stochastic dynamic system.
Methods: A stochastic production planning model is employed to cope with uncertainty and unexpected events to ensure a robust management strategy. Ito's formula describes the dynamic model for solving a stochastic differential equation. This paper uses stochastic optimal control theory to deal with efficient empty container management at the port yard. The findings have revealed the effectiveness of the proposed framework, which will provide a decision-making support scheme for efficient port operations.
Results: The presented algorithm is realized by a novel approach, employing the Hamilton-Jacobi-Bellman (HJB) equation for optimal stochastic control problems. When comparing the model with and without uncertainty events, the gap is just about 0.04 %, proving the robustness of the proposed model. The results provide a decision support system for port managers when managing the empty container in the seaport yard.
Conclusions: The proposed model not only figures out the optimal ordering of empty containers for each cycle but also points out the optimal safety stock level. Using a stochastic optimization approach, decision-makers can implement a strategic management policy to optimize seaport operational costs under market disruptions.

Keywords: Empty container management; Decision making; Inventory model; Stochastic optimal control; Hamilton-Jacobi-Bellman equation

INTRODUCTION

Marine transportation is the backbone of international trade and the most cost-effective way to move large quantities of goods and materials worldwide. With an estimated 90% of globalized trade by volume being carried out by sea transport, the maritime containerization market was projected to reach approximately 160 million TEUs (Twenty-foot Equivalent Units) in 2021 [UNCTAD, 2021]. Due to the dramatic increase in consumer demand for goods, the seaport terminals are the center of busy operations to ensure greater global supply chain resilience. More and more cargo will be filled in empty containers, and then the containers are transported between a terminal and the customer's location by trucks, trains, etc. Shipping companies always assume the responsibility for supplying freight containers to their customers. The inshore depot and the seaport yard are the two central locations where the empty container can be stored. The container management cost reached approximately 17 billion dollars [Boilé, 2006]. Besides, the global shipping industry estimated around 110 billion dollars per year on managing the containers (purchasing, leasing, maintenance, etc.). [Rodrigue, 2006]. Furthermore, the trade imbalance between each shipping route is the primary reason that causes the management of empty containers to become more intense. Table 1 illustrates the container volume for the major routes between 2020 and 2021 [UNCTAD,

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2021]. From Table 1, the number of containers on the route from Asia to North America and from Asia to Europe is outstanding and over 17 million TEUs, twice or three times larger than on other routes.

Table 1. Container volume on shipping routes over the period 2020-2021 (million TEUs)

Year	**Routes**			
	Asia – North America	**North America – Asia**	**Asia – Europe**	**Europe - Asia**
2020	20.6	6.9	16.9	7.2
2021	24.1	7.1	18.5	7.8

Recently, empty containers have been piled up in seaports worldwide due to the COVID-19 supply chain disruptions. The trade imbalance between the hub ports leads to the unpredictable stochastic demand for empty containers in each terminal. In particular, if the number is small, the port will lack empty containers, leading to time delays and higher shipping costs. The port will experience increased storage costs and congestion problems with many empty containers. The revenue or profit depends strongly on the container management policy. In addition, the stochastic environment is another crucial factor that makes container management more complex, in which unexpected events will impact maritime transportation and trade. The uncertainty includes frequent congestion or extreme weather that occurs at any stage of the supply chain. The recent pandemic is a potent risk to maritime transportation and trade. Discretions might negatively impact port operations, and cargo cannot be delivered to the consignee on time, resulting in a reliability problem for shipping enterprises. The management of empty containers has recently become surprisingly complicated and is one of the most challenging problems in maritime logistics. As a result, this issue has drawn significant attention from researchers who focus on mitigating supply chain disruptions efficiently and cost-effectively, discussed by [Abdelshafie et al., 2022]. The first group finds the shipping route that transports containers in the hinterland port or the seaport network. The second focuses on the number of empty containers from suppliers or other ports. The third group deals with a sub-problem or constraint under different decision-making strategies.

In the first group, some studies focus on reducing the transferability of empty containers between each terminal in ports by shipping enterprises. Depot-direct and street-turn policies introduced by [Jula et al., 2006] are two primary strategies for reallocating empty containers in the port network. As optimal tools for shipping lines to save management costs, the Inland-Depots-for-Empty-Containers (IDEC) system is employed to find storage nodes in the empty container supply chains attempting to decrease distance-related movement, fuel consumption and congestion in the port area proposed by [Mittal et al., 2013]. Otherwise, unloaded containers will be imported directly to ports to continue loading cargo, and this policy is known as the “street turn” introduced by [Furió et al., 2013]. To achieve the proposed policy, a substantial level of cooperation between each link in the supply chain network. On the one hand, the leasing industry exploded in the 1970s due to the economic benefit and flexibility tools to carriers, mainly because of the tremendous demand for empty containers investigated by [Theofanis et al., 2008]. The leasing container industry can be categorized into three main types: master lease, long-term lease, and short-term lease. Related to the final research group, long-term and short-term leasing decisions are compared to implement a realistic shipping network conducted by [Hu et al., 2020]. Each duty requires a similar and coincident time, type of cargo, shipping enterprise, and destination. In some cases, empty containers must be inspected (cleaning, repairing, etc.) before reusing them for the next cycle [Hoffmann et al., 2020]. Fig. 1 illustrates the generic container flows in the shipping network.

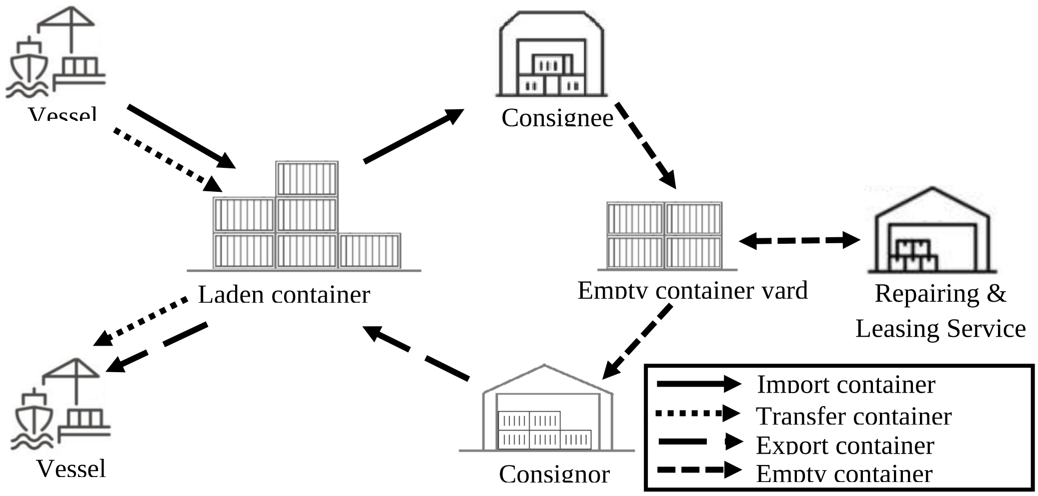

Fig. 1. Basic concepts of the generic container transport chain.

However, the studies focused on only one target for decision-making on the lease or repair and maintenance (R&M) of damaged containers without uncertainty. In addition, the latest articles deal with the deterministic scheme outnumbering compared to the stochastic approach. The deterministic models might be enough to realize optimal solutions for ideal cases without disruptions. [Di Francesco et al., 2009] proposed the deterministic mathematical model that examines multiple scenario policies' effect on empty container re-allocation. In contrast, uncertainty programming was offered to meet the time-dependent demand, supply, and capacity and minimize operation costs simultaneously presented by [Hosseini et al., 2018]. However, those studies may lack consideration if repairing and leasing costs are not routinely included in dynamic models. The liner shipping network problem has been introduced by [Shintani et al., 2007] for empty container repositioning. The study proposed a container shipping routing network using the Knapsack model approach with a Genetic Algorithm (GA) to optimize profit for the liner shipping enterprises. To extend the problem with the business flow approach, the two-layer collaborative optimization model was discussed by [Zhang et al., 2019]. This study addresses the decision-making problem by combining the tactical and operation layers. Within the framework of metaheuristic algorithms, [Belayachi et al., 2017] applied the heuristic method by neighborhood – Tabu Search (TS) to solve the transfer problem of empty containers from port to serve client demand. Particle Swarm Optimization (PSO) and GA are some of the most well-known techniques. There are also some combinations of inventory and mathematical programming models to solve complicated problems. In an inland transportation system, an inventory control problem was employed considering probabilistic demand and supply for the ordering and leasing policy proposed by [Yun et al., 2011].

Most existing studies are based on combining different models or optimization techniques to deal with empty container problems. Some studies introduced hybrid optimizations or enhanced traditional methods, which are inappropriate for a large-scale uncertain system. A four-echelon supply chain network was introduced under uncertainty with a hybrid mathematical model-based approach by [Douaioui et al., 2021]. To address the limitations and challenges outlined above, this article will explore different cost factors associated with the management of empty shipping containers, such as the fixed and variable costs involved in moving them and expenses related to ordering, repairing, leasing, and storing each container. To accomplish this, using a combination of inventory modeling and a methodology, the Hamilton-Jacobi-Bellman equation determines the optimal number of containers to order and the appropriate safety stock level for the seaport yard. Additionally, the study will incorporate stochastic optimal control and street turn policy to optimize the overall objective function more effectively.

The rest of this paper is organized as follows. Section 2 presents the dynamic models related to empty containers on the seaport yard by employing the inventory approach and the cost of the repositioning operation. Section 3 analyzes the problem using the HJB equation and introduces the proposed policy regarding optimality. Section 4 presents the numerical simulation of the optimization models with experimental data. Section 5 concludes this research and discusses the future direction of the research.

METHODOLOGY

The inventory model is typically used to optimize profit or cost problems by adapting the safety level introduced by [Li et al., 2015]. Some factors directly affect management costs, such as ordering costs, leasing costs, holding costs, repairing costs, etc. To calculate the optimal empty container level, this paper considers container deterioration over the holding period, leasing, the export demand, the uncertain imports of the container, and the stochastic factor at the seaport terminals. The dynamic model should accommodate those factors to explore a more realistic scenario when describing the superior stock level and optimal cost. Table 2 describes the critical variables with parameters to describe the multi-period empty container management problem and analyze inventory policies concerning distinct objectives.

Table 2. Notation and definition

$u(t)$	Number of empty containers being ordered each period
$x(t)$	Number of empty containers in the yard
$\hat{x}$	Goal or safety number of empty containers in the yard
$\omega_e(t)$	Number of empty containers exported from the yard
$\omega_i(t)$	Number of empty containers imported after unloading cargo
α	Coefficient of the damaged rate of a container after unloading cargo
$\beta_{x(t)}$	Coefficient of the deterioration of empty containers in the seaport
$I_{u(t)}$	Coefficient of the different prices when hiring the empty containers from the suppliers
γ	Coefficient of the number of containers being followed by the street-turn policy
$\varepsilon(t)$	Stochastic factors occurred in the operation of the seaport. (Delay time when importing empty containers)
c_o	Parameter of the ordering cost per container
c_l	Parameter of the leasing cost per container and day
c_h	Parameter of the holding cost per container and day
c_r	Parameter of the repairing cost per container

It is especially noteworthy that most previous studies on the inventory model do not consider the perturbation factor. Adding uncertainty to the yard model might demonstrate fluctuation and disturbance of all components, making the mathematical model more realistic at terminal ports. By incorporating stochastic disturbance for controlling empty containers, the dynamic model is described by Ito's approach to stochastic differential equation:

$$dx = \left[u(t) - \beta_{x(t)}x(t) - \omega_e(t) + \gamma\omega_i(t)\right]dt + \varepsilon(t)dz(t) \tag{1}$$

where the boundary condition is given by, $x(0) = x_0$, describing the starting number of containers in the seaport yard. The number also expresses the container capacity at the terminal port. The $\varepsilon(t)$ illustrates the stochastic component related to unexpected events in container management. The delay in loading and unloading goods might lead to the wrong number of empty containers and incompatibility between departments during operations. The street-turn policy is one of the crucial policies when managing the transportation of empty containers. This policy allows a carrier to use a container after unloading the goods rather than bringing them to the empty container yard. This container can be used directly to load the goods to prepare for transporting new goods. This strategy obviously saves cleaning costs, repair costs, and other costs. Using the street-turn policy will make yard management more effective through the warehouse model. To formalize the policy, there is always the proportion of containers unloaded without damaged use for the next period, where the parameter γ will denote the proportion. The empty container ordering cost is the expense that creates and processes orders to leasing companies.

$$O(u(t)) = c_o u(t),\ \ u(t) > 0 \tag{2}$$

Managing the number of empty containers is markedly tricky because many factors affect the exact number. To ensure the shipping time from the consignor to the consignee and increase the reliability of port operations, the container yard always provides that the number of empty containers in the yard is greater than the number of containers needed for the loading process at all times. Whenever the number of empty containers in the seaport yard is insufficient for the safety level, the manager will order the corresponding amount from the leasing company. In reality, the amount of leasing directly affects the management cost. For example, if the manager hires just one or two empty containers, the cost will eventually be more expensive than hiring many empty containers. Thus, the leasing cost is described as follows.

$$L(u(t)) = c_l I_{u(t)} u(t),\ \ u(t) > 0 \tag{3}$$

where $I_{u(t)}$ describes the percentage of the discount rate of container leasing price from the companies. A practical formula can be used to rent empty containers, considering percentage discounts when renting large containers; the more hiring numbers, the more discount value. The discount rate will be separated into two sides with 1000 TEUs as a middle point, and it is given as follows:

$$I_{u(t)} = \begin{cases} 1, & u(t) \geq 1000 \\ 0.7, & u(t) < 1000 \end{cases} \tag{4}$$

When too many empty containers are stored in the port yard, they will occupy many areas that reduce the storage capacity of the laden container, thus reducing the number of container transportation at the port. The holding cost covers all costs of each empty container in the yard, such as storage, depreciation, personnel, and rental space charge, and the more containers are stored, and the more the holding cost will account for. Hence, the holding cost is described as follows:

$$H(x(t), u(t), \omega_e(t)) = c_h \left(x(t) - \hat{x} - \omega_e(t) + u(t) \right)^2 \tag{5}$$

To make the model more realistic, the containers will be dirty and damaged for repair after each unloading of goods from the containers. Therefore, to use them for the subsequent loading of goods and long-term use, port authorities will spend the costs of repairing and cleaning containers. This leads to another extension of the primary problem.

$$R(\omega_i(t)) = \alpha c_r \omega_i(t) \tag{6}$$

Let $J(x(t), u(t))$ denote the expected value of the total cost per cycle, which comprises the leasing, holding, ordering, and repairing costs. After some algebraic manipulation, the inventory system's total cost per unit of time is obtained as follows.

$$J(x(t),u(t),\omega_e(t),\omega_i(t)) = E\left[\int_0^\infty \left(O(u(t)) + L(u(t)) + H(x(t),u(t),\omega_e(t)) + R(\omega_i(t))\right)dt\right]$$
$$= E\left[\int_0^\infty \left(c_o u(t) + c_l I_{u(t)} u(t) + c_h \left(x(t) - \hat{x} - \omega_e(t) + u(t)\right)^2 + \alpha c_r \omega_i(t)\right)dt\right] \quad (7)$$

STOCHASTIC OPTIMIZATION

The value function should satisfy the Hamilton-Jacobi-Bellman (or HJB) principle for a stochastic differential equation inspired by [Sethi, 2021]. The optimization problem is described as follows:

$$J = \min_{u(t)}\left[c_o u(t) + c_l I_{u(t)} u(t) + c_h \left(x(t) - \hat{x} - \omega_e(t) + u(t)\right)^2 + \alpha c_r \omega_i(t) + J_t \right.$$
$$\left. + \left(u(t) - \beta_{x(t)} x(t) - \omega_e(t) + \gamma \omega_i(t)\right) J_x + \frac{1}{2}\varepsilon^2(t) J_{xx} \right] \quad (8)$$

Recalling that the HJB equation depends on the value of $x(t)$, it is necessary to solve a set of equations for the case of $x(t) \geq 0$. There is still a certain number of empty containers in the seaport yard, which leads to $\beta_{x(t)} x(t) > 0$. Otherwise, $x(t) < 0$ the terminal port might have an empty container to serve the demand. Therefore, the optimal solution for decision-making can be realized by employing the stochastic optimal control theory.

Theorem 1: If there is no constraint on the control input $u(t)$, then the optimal order number of empty containers at the seaport yard is described as the following equation:

$$u^*(t) = -\frac{\left(3 + 2\beta_{x(t)} + S\right)\left(e^{(T-t+C_1)S} - 1\right)}{2\left[1 - \left(e^{(T-t+C_1)S}\right)\dfrac{\left(3+2\beta_{x(t)}\right)+S}{\left(3+2\beta_{x(t)}\right)-S}\right]} x(t)$$
$$-\frac{1}{2c_h P}\left(\frac{PB - 2Q(t)N - 2c_h\left(A - \omega_e(t) - \hat{x}\right)}{e^{P(T-t+C_2)}} + 2Q(t)N + 2c_h\left(A - \omega_e(t) - \hat{x}\right)\right) \quad (9)$$
$$+\frac{-c_o - c_l I_{u(t)} + 2c_h\left(\omega_e(t) + \hat{x} - x(t)\right)}{2c_h}$$

where

$$S = \sqrt{(3+2\beta_{x(t)})^2 + 4},\ P = \left(2 + \frac{Q(t)}{c_h} + \beta_{x(t)}\right),\ N = \left(\gamma\omega_i(t) - \frac{c_o + c_l I_{u(t)}}{2c_h} + \hat{x}\right),\ Q(t) > 0$$

Proof See Appendix 1 for more details.

According to Theorem 1, the number of empty containers is optimal. In practice, the ordering number of empty containers will be non-negative; thus, a boundary being set in minimum is zero. Moreover, the safety number of containers stored in the seaport yard is positive for serving the demand for empty containers. The optimal strategy should focus on minimizing the management cost and guaranteeing the number of containers within the safety range. Hence, an optimal policy is described as follows:

$$u(t) = \max\left[0, -\frac{\left(3+2\beta_{x(t)}+S\right)\left(e^{(T-t+C_1)S}-1\right)}{2\left[1-\left(e^{(T-t+C_1)S}\right)\frac{\left(3+2\beta_{x(t)}\right)+S}{\left(3+2\beta_{x(t)}\right)-S}\right]}x(t) - \frac{1}{2c_h P}\left(\frac{PB-2Q(t)N-2c_h\left(A-\omega_e(t)-\hat{x}\right)}{e^{P(T-t+C_2)}}+2Q(t)N+2c_h\left(A-\omega_e(t)-\hat{x}\right)\right) + \frac{-c_o-c_l I_{u(t)}+2c_h\left(\omega_e(t)+\hat{x}-x(t)\right)}{2c_h}\right] \quad (10)$$

Using Karush-Kuhn-Tucker (KKT) conditions and the inequality constraint $u(t) \geq 0$ [Sethi, 2021], the optimal ordering number of empty containers is given in equation (10). It is worth noting that the KKK condition describes the optimality requirement in dynamic programming. Therefore, the optimal ordering policy can be determined by Theorem 1.

SIMULATION RESULT AND DISCUSSION

Numerical analysis is conducted on a personal computer with an AMD Ryzen 5 5600G processor, a base clock speed of 3.9 GHz, and 16 GB RAM. A code used for simulation results is built into the MATLAB program. All data used in the simulation have been collected from the port authority of Busan Port, which ranked sixth in the world's container throughput and is the primary port in South Korea. A numerical simulation is carried out for the evaluation of the proposed model. Input data are given in Tables 3 and 4 based on the fundamental market analysis and are typical in port operations. The experiment is sampled with 3650 days, starting from an initial value of 3000 TEUs.

Table 3. Summary statistics for numerical analysis

Types of data	Source	Numerical evaluation
ordering costs	market analysis	[$1-5]/TEU
holding costs	market analysis	[$1-5]/TEU/day
leasing costs	market analysis	[$5-20]/TEU/day
repair distribution	industry interviews	Poisson Distribution
repair costs	market analysis	[$50-300]/TEU
street-turns	industry interviews	[0-30%] of a container after unloading cargo

The demand is based on data from leasing companies near Busan Port. The exponent distribution can be described as the number of empty containers in the seaport yard. The trending exporter demand is increased by following the simulation time:

$$\omega_e(t) = 1500 + 200\sin\left(\frac{t}{70}+4\right) + e^{0.002t} + rand(100, 500) \quad (11)$$

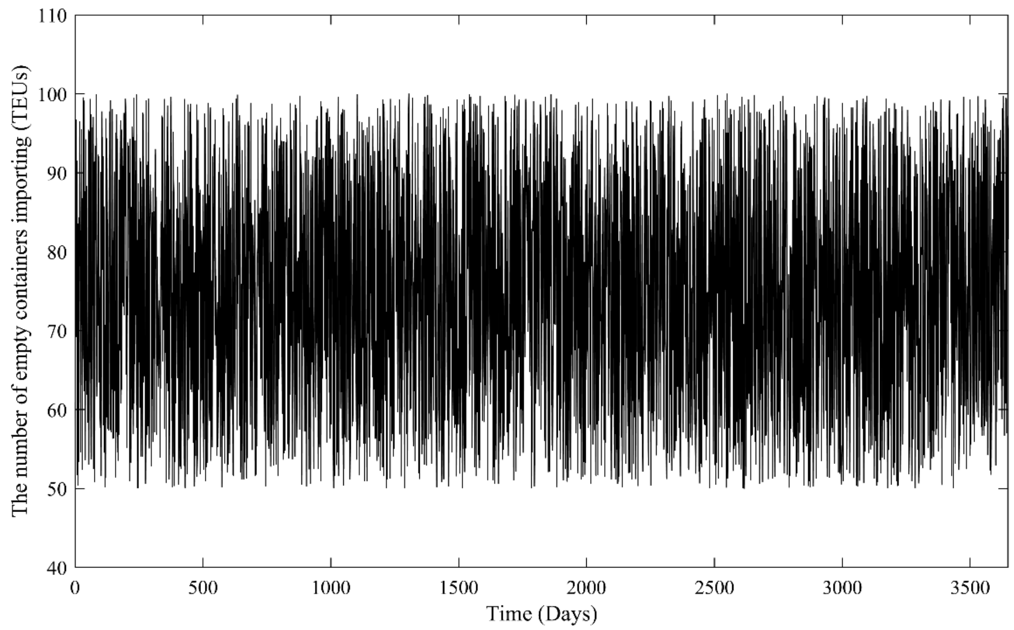

Fig. 2. The number of empty containers after unloading cargo

In this scenario, the volume of empty containers importing after unloading cargo fluctuates between 50 and 100 TEUs daily. There are a lot of unexpected events occurred during the unloading stage. Obviously, the importing or exporting numbers often fluctuate unpredictably as these numbers impact transportation costs. In this case, the parameter will be described as random numbers from the uniform distribution on the interval shown in Fig. 2. The stochastic variable will be expressed as the Gaussian distribution demonstrating unexpected container shipping events. The parameter values are given in Table 4, prepared for the numerical simulation that illustrates stochastic events. All the values are selected by the many experiment tests, and some are typical in port operations.

Table 4. Parameter values for numerical analysis.

Parameter	α	β	γ	x_0	c_o	c_l	c_h	c_r
Value	0.2	0.02	0.7	3000	2	10	2	200

For the setting of the given parameter, the numerical test is performed based on changing the safety stock levels in the yard from 1000 TEUs to 4000 TEUs. The computed costs are summarized in Table 5, where the holding costs account for most of the costs of container management. Changing the safety stock levels gives the total management cost according to the parabolic shape. Therefore, the safety level is determined to optimize the management cost for the seaport operations. When the safety level is lower, the cost of renting empty containers will increase to meet the demand. On the contrary, more empty containers will be stored in the seaport yard when the safety level is higher. Then it will increase the holding cost.

Table 5. Operational cost analysis considering a different number of safety levels of empty containers (Unit: Thousand USD)

Safety level $\hat{x}$	1000	1500	2000	2500	3000	3500	4000
Holding cost	2500.5	1031.5	538.9	259.7	191.1	336.1	694.7
Total cost	5069.4	4992.4	4974.8	4975.7	4998.2	5040.4	5102.2

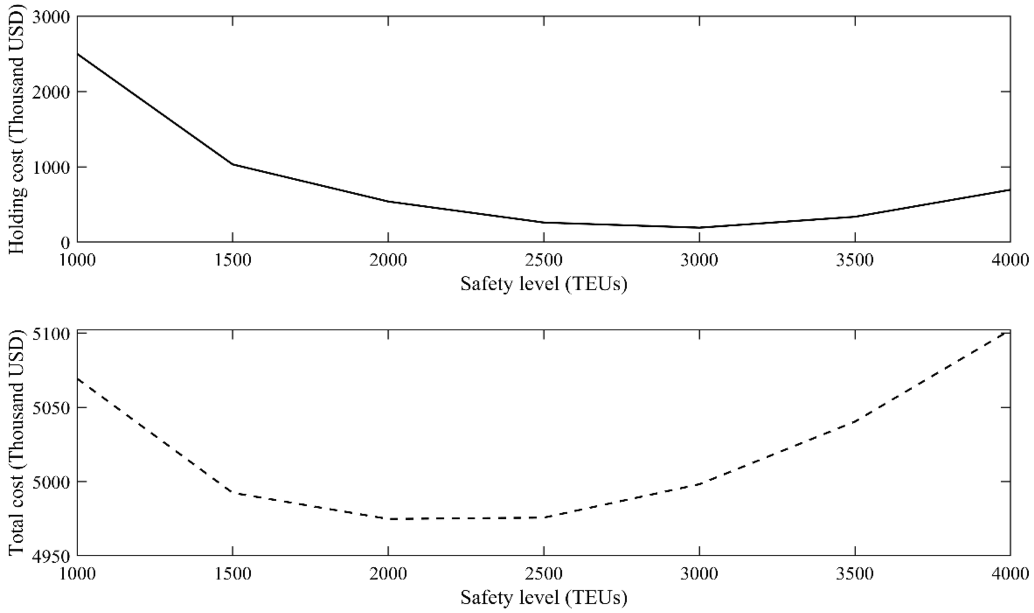

Fig. 3. Cost change for different safety levels ($\hat{x}$).

With gradually increasing safety levels, the holding cost and total cost for managing empty containers in the yard are calculated as shown in Table 5 and Fig. 3. When the number of safety empty containers slightly increases from 1000 TEUs to 4000 TEUs, and there is a significant decrease in the operational costs. It then reaches the lowest point, approximately 191.1 thousand dollars at 3000 TEUs and 4975.7 thousand dollars at 2500 TEUs, respectively. The holding cost witnesses a minimal growth to about 694.7 thousand dollars at the safety level of 4000 TEUs. The total cost dramatically rises to 5102.2 thousand dollars at the same safety level. These findings illustrate the sensitivity of the costs when the safety level changes. Furthermore, the test results can provide information on the safety level needed for optimizing yard operational costs.

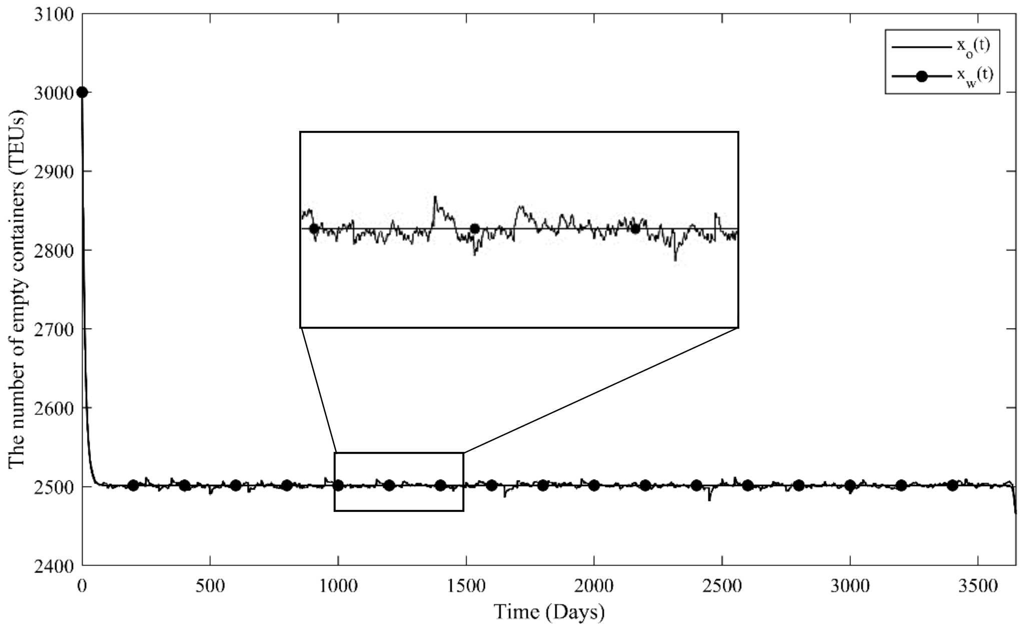

Fig. 4. Number of empty containers with and without stochastic components with a safety level of 2500 TEUs.

Fig. 4 presents the comparative analysis of the operational costs with (x_o) and without (x_w) stochastic events. Under the optimal ordering policy, the number of empty containers $x_o(t)$ decreased from the initial value of 3000 TEUs to the expected number of 2500 TEUs in 30 days. Then it fluctuated around the expected number until the end of the period. Without stochastic factors $x_w(t)$, the terminal operation is stable from the beginning until the end of the simulation period. With optimal ordering strategy, the total cost is calculated as 5714.8 thousand dollars which is a little bit bigger compared to the total cost without random variables in the dynamic model, as 5712.9 thousand dollars. The efficacy of the proposed model is illustrated in Fig. 4, where the actual number of empty containers fluctuates around the ideal value unaffected by the stochastic disturbance. The percentage of the difference between the management cost with and without uncertainty components is approximately 0.04 %, which might prove the effectiveness of the proposed model. Especially the number of empty containers approaches the desired safety level rapidly and keeps the safety level with little variability until the end of the period. The findings have revealed the effectiveness of the proposed framework, which will provide a decision-making support scheme for efficient port operations.

Next, the street-turn analysis based on the safety level at the seaport terminal is given in Table 6 and Fig. 5. The change in the street-turn coefficient directly affects the total cost. At a hundred percent with a safety level of 2500 TEU, the optimal management cost is approximately 4960.3 (thousand USD). However, the street-turn coefficient never reaches the maximum ratio in practice because an unexpected event when unloading might cause damage to the container. Fig. 5 shows that the percentage increase in the street-turn coefficient may bring further costs down. The optimal safety level and the coefficient value for the percent street-turn policy are determined by the results from Figs. 3 and 5. Efforts to maximize the coefficient might result in the optimal cost in the short-term period. However, it is not the best option in the long term since containers have been in use for an extended period, leading to increased repair costs and total costs. Additionally, Fig. 4 illustrates the efficiency of the proposed method when simulating with and without uncertainty considerations in the built model.

CONCLUSION

This study employs the inventory model to consider the stochastic optimization method to manage empty containers in the seaport yard. The repairing option for damaged containers and street-turn policy are incorporated in formulating objective functions. Based on the stochastic optimization method, the optimal number of ordering empty containers is implemented by solving the stochastic HJB equation. Furthermore, numerical experiments are provided to evaluate the efficiency and capability of the proposed strategies. By comparing the dynamic model with and without uncertainty components, the gap is just about 0.04 %, which might prove the robustness of the proposed model. Using a stochastic optimization approach, decision-makers can realize strategic management policy to optimize operational costs. The main goal of this study is to find the decision support system to solve the empty container management in the seaport yard. This study has limitations due to constraints, methodology, materials, etc. For the model to be more applicable in real-world scenarios, emissions and fuel consumption should be considered in the dynamic model to deal with problems like greenhouse gas emissions and global warming, imposing additional costs such as emissions costs. Additionally, the study could benefit from employing a method to approximate the exporter demand function to bridge the gap between theory and practical application. These issues can be solved in future research using an upgraded methodology.

Table 6. Total costs considering the different safety levels of the empty container and the street-turn coefficient in the seaport yard. (Unit: thousand USD).

Safety level $\hat{x}$	Street-turn coefficient γ	Total cost
1000	0.5	5125.7
	0.6	5118.1
	0.7	5110.8
	0.8	5103.2
	0.9	5095.7
	1.0	5088.2
1500	0.5	5014.3
	0.6	5006.6
	0.7	4998.9
	0.8	4991.2
	0.9	4983.5
	1.0	4975.8
2000	0.5	4997.0
	0.6	4989.4
	0.7	4981.8
	0.8	4974.2
	0.9	4966.7
	1.0	4959.1

Safety level $\hat{x}$	Street-turn coefficient γ	Total cost
2500	0.5	4997.6
	0.6	4990.2
	0.7	4982.6
	0.8	4975.2
	0.9	4967.7
	1.0	4960.3
3000	0.5	5020.2
	0.6	5012.9
	0.7	5005.5
	0.8	4998.1
	0.9	4990.8
	1.0	4983.5
3500	0.5	5062.5
	0.6	5055.3
	0.7	5048.0
	0.8	5040.8
	0.9	5033.6
	1.0	5026.4
4000	0.5	5124.4
	0.6	5117.3
	0.7	5110.2
	0.8	5103.1
	0.9	5096.0
	1.0	5088.9

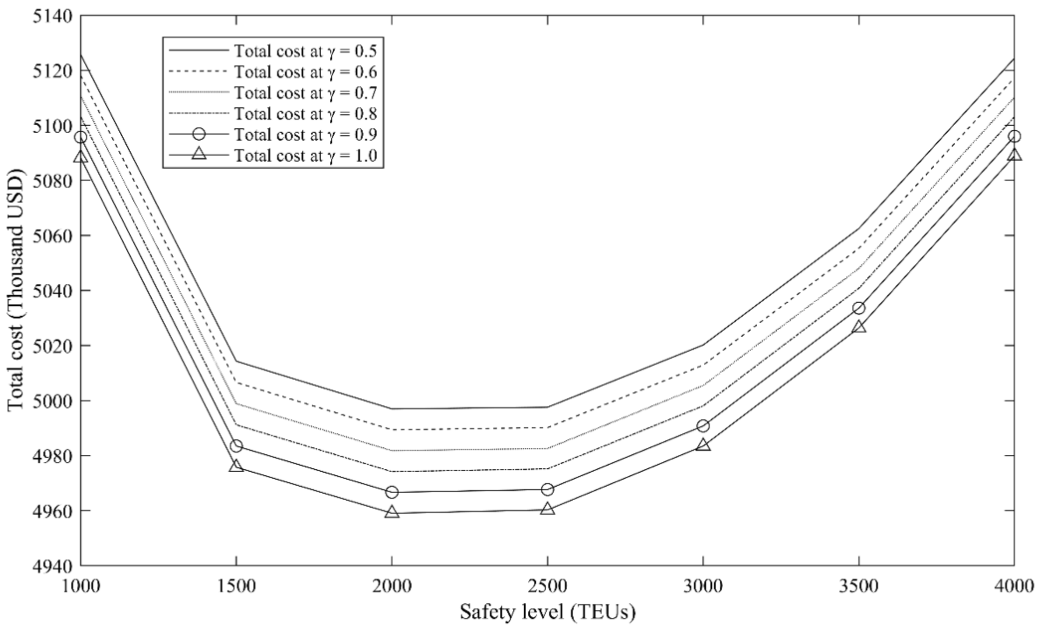

Fig. 5. Total costs with different safety levels and street-turn coefficients.

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APPENDIX 1. PROOF OF THEOREM 1

Proof Equation (8) takes the quadratic function of the control input $u(t)$ having no boundary. The optimal solution can be obtained by taking its derivative concerning u, and setting them to zero,

$$c_o + c_l I_{u(t)} + 2c_h\left(x(t) - \hat{x} - \omega_e(t) + u(t)\right) + J_x = 0 \tag{12}$$

Then, the control input can be given by

$$u^*(t) = A - \frac{J_x}{2c_h} \tag{13}$$

where $A\left(x(t), \omega_e(t)\right) = \frac{-c_o - c_l I_{u(t)} + 2c_h\left(\omega_e(t) + \hat{x} - x(t)\right)}{2c_h}$, and $c_h > 0$. Substituting the optimal decision policy (13) into equation (8) leads to,

$$\begin{aligned} J(x(t)) = & -\frac{J_x^2}{4c_h} + \left(-\frac{c_o + c_l I_{u(t)}}{2c_h} - \left(1 + \beta_{x(t)}\right)x(t) + \hat{x} + \gamma\omega_i(t)\right)J_x + \frac{1}{2}\varepsilon^2(t)J_{xx} \\ & + J_t + A\left(c_o + c_l I_{u(t)}\right) + c_h\left(x(t) - \omega_e(t) - \hat{x} + A\right)^2 + \alpha c_r \omega_i(t) \end{aligned} \tag{14}$$

Next, it is noted that $J(x)$ is the objective function to be minimized. The non-linear differential equation can be solved by considering a quadratic concave function candidate,

$$\begin{aligned} & J(x(t)) = Q(t)x^2 + R(t)x + M(t) \\ & J_t = \dot{Q}x^2 + \dot{R}x + \dot{M},\ \ J_x = 2Qx + R,\ \ J_{xx} = 2Q \end{aligned} \tag{15}$$

where $Q(t)\,(>0)$, $R(t)$ and $M(t)$ can be determined for the minimum value. Substituting (15) into (14) yields

$$
\begin{aligned}
0 = & \left[\dot{Q} - \frac{Q^2(t)}{c_h} - \left(1 + 2\left(1 + \beta_{x(t)}\right)\right) Q(t) + c_h \right] x^2(t) \\
& + \left[\dot{R} - \left(2 + \frac{Q(t)}{c_h} + \beta_{x(t)} \right) R(t) + 2Q(t) \left(\gamma \omega_i(t) - \frac{c_o + c_l I_{u(t)}}{2c_h} + \hat{x} \right) + 2c_h \left(A - \omega_e(t) - \hat{x} \right) \right] x(t) \\
& + \dot{M} - M(t) - \frac{R^2(t)}{4c_h} + R(t) \left(\gamma \omega_i(t) - \frac{c_o + c_l I_{u(t)}}{2c_h} + \hat{x} \right) + \varepsilon^2(t) Q(t) + A\left(c_o + c_l I_{u(t)} \right) \\
& + c_h \left(A - \omega_e(t) - \hat{x} \right)^2 + \alpha c_r \omega_i(t)
\end{aligned} \tag{16}
$$

Solving equation (16) gives

$$
\begin{cases}
\dot{Q} = \dfrac{Q^2(t)}{c_h} + \left(1 + 2\left(1 + \beta_{x(t)}\right)\right) Q(t) - c_h \\
\dot{R} = \left(2 + \dfrac{Q(t)}{c_h} + \beta_{x(t)} \right) R(t) - 2Q(t) \left(\gamma \omega_i(t) - \dfrac{c_o + c_l I_{u(t)}}{2c_h} + \hat{x} \right) - 2c_h \left(A - \omega_e(t) - \hat{x} \right) \\
\dot{M} = M(t) + \dfrac{R^2(t)}{4c_h} - R(t) \left(\gamma \omega_i(t) - \dfrac{c_o + c_l I_{u(t)}}{2c_h} + \hat{x} \right) - \varepsilon^2(t) Q(t) - A\left(c_o + c_l I_{u(t)} \right) \\
\quad - c_h \left(A - \omega_e(t) - \hat{x} \right)^2 - \alpha c_r \omega_i(t)
\end{cases} \tag{17}
$$

The dynamical system (17) represents a hierarchical system of equations. The time evolution of the function $R(t)$ contains the function $Q(t)$, while the function $M(t)$ includes two functions $Q(t)$ and $R(t)$. The non-linear systems can be solved for different cases of $x(t)$ with the following terminal conditions: $Q(t) = 0$, $R(t) = B$, and $M(t) = 0$, where B is constant. Solving equation (17) yields

$$
\begin{cases}
Q(t) = \dfrac{c_h \left(3 + 2\beta_{x(t)} + S\right)\left(e^{(T-t+C_1)S} - 1\right)}{2\left[1 - \left(e^{(T-t+C_1)S}\right) \dfrac{\left(3 + 2\beta_{x(t)}\right) + S}{\left(3 + 2\beta_{x(t)}\right) - S}\right]} \\
R(t) = \dfrac{1}{P}\left(\dfrac{PB - 2Q(t)N - 2c_h \left(A - \omega_e(t) - \hat{x}\right)}{e^{P(T-t+C_2)}} + 2Q(t)N + 2c_h \left(A - \omega_e(t) - \hat{x}\right) \right) \\
M(t) = \dfrac{\dfrac{R^2(t)}{4c_h} - R(t)N - \varepsilon^2(t)Q(t) - A\left(c_o + c_l I_{u(t)}\right) - c_h \left(A - \omega_e(t) - \hat{x}\right)^2 - \alpha c_r \omega_i(t)}{e^{T-t+C_3}} \\
\qquad - \dfrac{R^2(t)}{4c_h} + R(t)N + \varepsilon^2(t)Q(t) + A\left(c_o + c_l I_{u(t)}\right) + c_h \left(A - \omega_e(t) - \hat{x}\right)^2 + \alpha c_r \omega_i(t)
\end{cases} \tag{18}
$$

where C_1, C_2, and C_3 are constants that can be determined from terminal conditions. Finally, employing equations (13), (15), and (18) with no boundary on the control input $u(t)$ yields,

$$u^*(t) = -\frac{\left(3+2\beta_{x(t)}+S\right)\left(e^{(T-t+C_1)S}-1\right)}{2\left[1-\left(e^{(T-t+C_1)S}\right)\frac{\left(3+2\beta_{x(t)}\right)+S}{\left(3+2\beta_{x(t)}\right)-S}\right]}x(t)$$
$$-\frac{1}{2c_hP}\left(\frac{PB-2Q(t)N-2c_h\left(A-\omega_e(t)-\hat{x}\right)}{e^{P(T-t+C_2)}}+2Q(t)N+2c_h\left(A-\omega_e(t)-\hat{x}\right)\right) \quad (19)$$
$$+\frac{-c_o-c_lI_{u(t)}+2c_h\left(\omega_e(t)+\hat{x}-x(t)\right)}{2c_h}$$

The proof of Theorem 1 is completed.

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ORIGINAL PAPER

PROMOTING HEALTHCARE TECHNOLOGIES THROUGH SUSTAINABLE SUPPLY CHAIN OPERATIONS: AN EMPIRICAL ANALYSIS OF KEY SUCCESS FACTORS USING THE ISM-MICMAC APPROACH

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Abstract. This study analyses key successful factors (KSFs) affecting health supply chains using a novel ISM-MICMAC methodology. Initially, KSFs were collected from past articles, which were later analyzed through the ISM-MICMAC methodology. Healthcare technologies (HCTs) are regarded as innovative and fastest-growing technologies and have seen advancement in the last few decades. Successful and sustainable delivery of health services is only possible through an effective supply chain and logistics network. However, HCTs confront pressure in healthcare supply chains due to different issues. Therefore, it is essential to evaluate KSFs affecting the successful delivery of HCTs supply chains. After obtaining data from experts, interpretive structural modeling (ISM) results indicated that initial capital, top management commitment, training & experience, new technology and information, information quality, and strategic partnership with suppliers are the most crucial KSFs HCTs supply chain in the Pakistani context. Furthermore, MICMAC analysis categorized KSFs with the help of their driving and dependence power. These results support health strategists and policymakers to understand the severity of the identified top five KSFs and act as a moderator to take care of these KSFs, which would ultimately contribute to the successful delivery of the health care supply chain and improvement of critical health services. This study's results would also be helpful for the supply chain managers of the manufacturing industry in the Pakistani context. This research is one of the initial studies to precisely explore KSFs affecting health supply chains using a novel ISM-MICMAC and categorize KSFs with the help of their driving and dependence power by applying MICMAC analysis in the Pakistani SCM context.

Keywords: Management, environment, key success factors; review; healthcare supply chain; logistics; health sector, sustainability, sustainable supply chain management

INTRODUCTION

Healthcare technologies (HCTs) help to improve and protect the lives of affected individuals from different diseases (N. C. f. H. Statistics, 2010). This sector has a comprehensive range of products such as hospitals, beds, blankets, syringes, injections, sticking plasters, tablets, latex gloves, and syrups; mobility items such as wheelchairs, walkers, scooters, hearing aids items; personal care aids items such as dressing bandages, commodes, and bath chairs; high technology equipment such as joints replacement for hips and knees, pacemakers, ventilators, intelligent contact lenses and kidney machines (Hartford, 2014). The industry of HCTs is perceived as advanced, fast-growing, and artistic across the world, especially in developed countries such as Germany, the United States of America (USA),

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Canada, the United Kingdom (UK), and China (Okpala, 2018; Vogenberg & Santilli, 2018). However, Pakistan has approximately 800 healthcare equipment production units exporting items worth more than $200 million to over 60 countries (Waheed, 2017). Pakistan's healthcare expenditure is $9.2 billion (H. Ali, 2016), and the direct and indirect workforce employed by this industry is approximately more than 0.5 million (Ahmed & Batool, 2017). Pakistan has 1219 hospitals, 733 rural health centers (RHCs), 5345 primary health units (BHUs), 5654 dispensaries, and 727 maternity & child welfare centers (MCWC), and 127807 beds (P. B. o. Statistics, 2017). Despite the remarkable developments in the healthcare industry internationally, the Pakistani healthcare production industry faces several challenges in its supply chain operations due to deficiencies in supply chain management (SCM) infrastructure (Khan, Razzaq, Yu, & Miller, 2021) and (Fahimnia, Jabbarzadeh, Ghavamifar, & Bell, 2017). Although the public has continuous pressure on the government to reduce the prices of medicines and fees, on the other hand, the expenditure on HCTs is higher (Jamshed, Hassali, Ibrahim, & Babar, 2011).

Furthermore, to sustain and increase the market share, healthcare product manufacturers depend on their product innovation and face different issues, e.g., the short lifecycle of products, the limited period for new product development, and approvals from regulatory authorities (de Faria & Wieck, 2015; Thatte, Hussain, de Rosas-Valera, & Malik, 2009). Moreover, Chinese, German, and Indian medical firms are also lined up in the Pakistani healthcare industry to capture the market with cost-efficient products and force Pakistan manufacturing firms to produce and distribute low-cost products globally (Nadvi & Halder, 2005). In the current situation, research discussing healthcare SCM has become critical. The demand for the advancement of healthcare aids products delivery systems has gained greater attention from professionals because of apparent failures in medical aid delivery systems (Kumar, Dieveney, & Dieveney, 2009; Pettit & Beresford, 2009; Scheibe & Blackhurst, 2018). García-Villarreal, Bhamra, and Schoenheit (2019) found a shortfall of defined strategies of SCM in the healthcare sector. The primary deficiencies were reported to be a lack of efficient planning, lack of top management support, lack of sales forecasts, lack of formulated strategies, and lack of coordination with suppliers and processes during the pandemic outbreak (Khan, Yu, Umar, de Sousa Jabbour, & Mor, 2021).

Generally, logistics activities in emergency and critical situations are frequently significant and challenging for healthcare SC (Haszlinna Mustaffa & Potter, 2009). For an effective and successful supply chain, there should be a great and robust understanding of barriers and drivers directly or indirectly involved in the processes. Increasing the SC's efficiency needs uncertainty to be decreased or even removed from its operations; however, this may not be wholly eradicated in many healthcare cases (Hasani, Zegordi, & Nikbakhsh, 2015). These barriers and issues are severe in the healthcare SC scenario when products provide relief to patients in critical situations, control and expedite healthcare product delivery, and efficient SC infrastructure is inevitable. Identifying the key success factors (KSFs) attached to a healthcare SC is vital to develop a more robust understanding of the issues impeding SC's effective implementation. However, as compared with commercial SC, there are certain KSFs that contribute to the ultimate success of HCTs and healthcare product delivery. Considering the shortage of studies concerning KSFs in the health care supply chain in developing countries, lower attention to medication errors, and wrong product delivery in an emergency, the primary objectives of this study are:

- To evaluate the main KSFs in the healthcare supply chain in previous studies
- To formulate a contextual connection among KSFs as well as form their hierarchical structure
- To classify the selected KSFs according to their driving and dependence power

According to the literature, the author's first attempt to identify the KSFs in Pakistani healthcare SC by using ISM and MICMAC analysis. Initially, KSFs were identified from the extensive literature through experts' opinions, and this issue is related to multiple-criteria decision-making (MCDM). Therefore, the levels of the hierarchal structure of KSFs were calculated by applying ISM and MICMAC to evaluate their contextual relationship through driving and dependence power.

This research extended the literature in the Pakistani context in the following ways:

- Initially, this research classifies the main KSFs in the healthcare supply chain in the Pakistani context. The identified KSFs can be considered a foundation that can be removed on a priority basis to implement the healthcare sector's supply chain effectively.
- Secondly, the combination of ISM and MICMAC analysis is suggested to evaluate KSFs in healthcare SC. This study adds theory because the recommended method is rationally and practically solid to evaluate KSFs and verify their findings in different contexts.
- Lastly, this research will be regarded as a standard to effectively help supply chain managers and government authorities implement KSFs in healthcare SC.

The rest of the article is organized in the following sections: a literature review is displayed in section 2; section 3 portrays a brief methodology overview. Results, analysis of data, and discussions under the light of detailed literature on KSFs in healthcare SC are presented in section 4.

LITERATURE REVIEW

In the literature review, the field of SCM performed exceptionally well in operation management (Waqas, Honggang, Ahmad, Khan, & Iqbal, 2021). However, after searching the detailed literature, limited literature was focused on identifying KSFs of healthcare SCM (García-Villarreal et al., 2019); Yadav & Singh, 2020). Unfortunately, no study has been found to identify KSFs in Pakistan healthcare technology SC.

The supply chain is "A process involving three or more parties in the smooth flow of products, services, or information from origin to the customer"(Schäfer, 2022). Three significant parties in the healthcare supply chain are as follows 1. Producers (companies involved in manufacturing HCTs, manufacturing companies in health care including pharmaceutical companies, producers of medical and surgical instruments, and lastly, medical devices); 2. Purchasers (purchasing agents, e.g., distributors, government, or public organizations) and 3. Health care service providers (e.g., hospitals).

Furthermore, in this process, customers and financial intermediaries also create an important role as local government, patients and individuals are customers, and insurance companies, banks, and health maintenance organizations are financial intermediaries. More details can be found in Figure1. Elhidaoui, Benhida, El Fezazi, Kota, and Lamalem (2022) and Smith, Nachtmann, and Pohl (2012) provided a more comprehensive picture of the health care supply chain by showing the leading players involved and product flow in a single place. The detailed healthcare supply chain is shown in Figure 2.

Key success factors (KSFs)

Daniel (1961) introduced the concept of KSFs in his study. Huotari and Wilson (2001) proposed that if certain KSFs become critical within any organization, the chances of failure of that organization would increase. Although in the context of HCTs and the healthcare supply chain, profit is not considered a primary motive of the supplier. If KSFs are not defined well, failure might be expected in the delivery process of healthcare products to whom they are required in an emergency, or the distribution of wrong products may also happen (Vaz & Araujo, 2022). Different researchers have put forward various definitions of KSFs. Every business has its key factors. Their proper identification and implementation can ensure any business's better performance in any market (Rockart, 1979). According to (Zaman, Wang, Rasool, uz Zaman, & Raza, 2022), these identified factors are KSFs and elaborate them as different activities or processes that should receive greater attention from top management for successful implementation. (Guerrero, Gómez, Victorica, López, & Fong, 2022) found that KSFs are those activities that ensure achieving a distinctive business position in the market. Identification and implementation of KSFs at the initial stages of formulation of strategies can increase the business performance and help the top management allocate resources and monitor the business activities better (Thomassey, 2010). The concept of KSFs has been applied successfully in different domains. In literature, research papers on KSFs can be found on project management (Rasool et al., 2022), epidemic emergency management systems (Song, Zhao, Mubarak, & Taresh, 2022), information management systems (Muhammad, Miah, Isa, & Samsudin, 2022), supply chain management (Power, Sohal, & Rahman, 2001), knowledge management (Akhavan, Jafari, & Fathian, 2006), brownfield redevelopment (Ahmad, Zhu, Shafait, Sahibzada, & Waheed, 2019; Weng, Zhu, Song, & Ahmad, 2019), public-private partnerships (PPP) (Kavishe & Chileshe, 2018), total quality management (TQM) (Seetharaman, Sreenivasan, & Boon, 2006) and (Khan, Godil, Yu, Abbas, & Shamim, 2021), implementation of six sigma initiatives (Fadly Habidin & Mohd Yusof, 2013), implementation, execution and adoption of Internet-of-Things (IoT) systems (Luthra, S., Berwal, Y. P. S., & Motia, K., 2021), adoption of Social Media Marketing Technology (SMMT) by Micro, Small, and Medium Enterprises (MSMEs) (Eze, S. C., Chinedu-Eze, V. C., & Awa, H. O., 2021), use of e-learning in higher education (Priatna, T., Maylawati, D., Sugilar, H., & Ramdhani, M. (2020), and among many others fields.

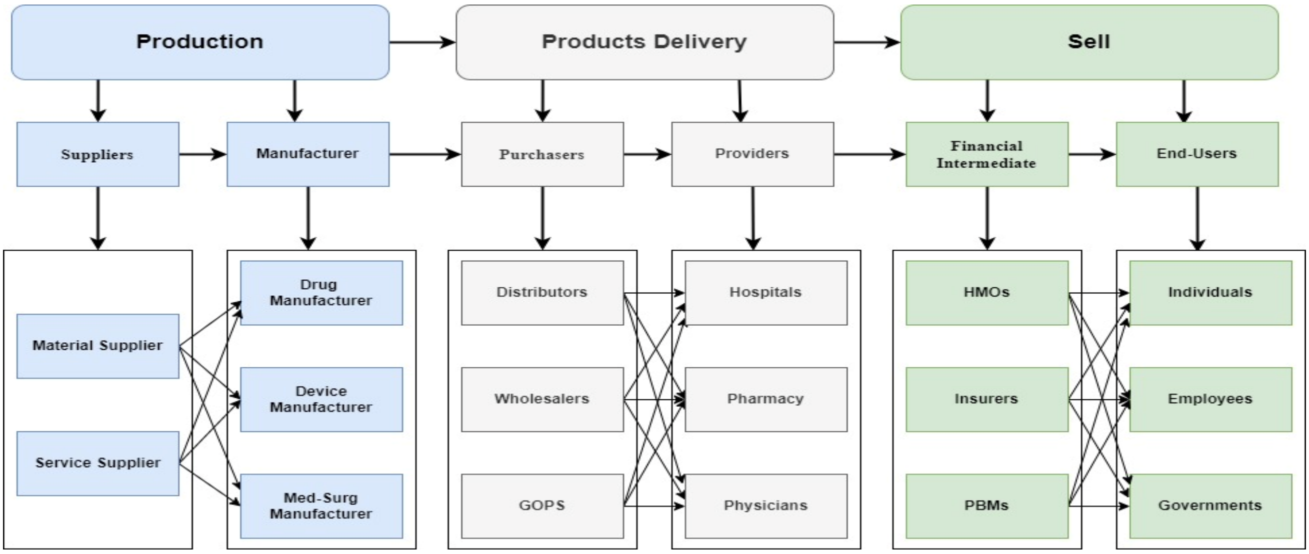

Fig 1. Value chain of the healthcare industry

KSFs in supply chain management and healthcare sector

The implementation of KSFs in the field of SCM is limited. Although few earlier studies on the performance of KSFs in this healthcare have been found, no analysis has been found in Pakistan. Power et al. (2001) investigated 962 manufacturing firms in Australia to identify and verify KSFs that differentiate organizations from more agile to less agile. In handling SCM, the following are the proposed factors in their study: "agile supply chain, supplier relations, computer-based technologies, technology utilization, just-in-time methodology, resource management, continuous improvement enablers, participative management style, customer satisfaction, product innovation, and delivery performance." According to Tan, Yen, and Fang (2002), KSFs customer-centric strategy, people's commitments, improved or redesigned process, software, technology, and infrastructure to supply chain management in the E-commerce arena.

(Heydari & Bakhshi, 2022) researched the selection of small third-party logistics providers in the manufacturing industry of Hong Kong. (Wuni & Shen, 2022) identified the top five critical success factors for an efficient small third-party logistics provider systems, such as information technology, strategic planning, capacity planning, inventory management, and transportation system. (Atıcı, Adem, Şenol, & Dağdeviren, 2022) Examined the KSFs for enterprises' resource utilization. They identified the nine most critical barriers to organization resource implementation: correspondence, process, interaction and expectation success, organizational relating, IT infrastructure, strategic relating, managerial relating, and operational relating. (Thomassey & Zeng, 2021) highlighted CSFs for web-based SCM. They uncovered the top five factors using exploratory factor analysis (EFA): communication, education and training, hardware and software reliability, top management commitment, and data security. Rao Tummala, Phillips, and Johnson (2006) comprehensively addressed operational KSFs related to SCM implementation in the manufacturing industry. They identified the following essential factors: Improving inventory, reducing the cost of operations, cross-functional communication, creating corporate culture lead time, and customer satisfaction. According to Kuei, Madu, and Lin (2008) findings, SC leadership's quality, relationship with suppliers, consumer focus, quality of IT system, and focus on integration process are identified CSFs for SC quality management.

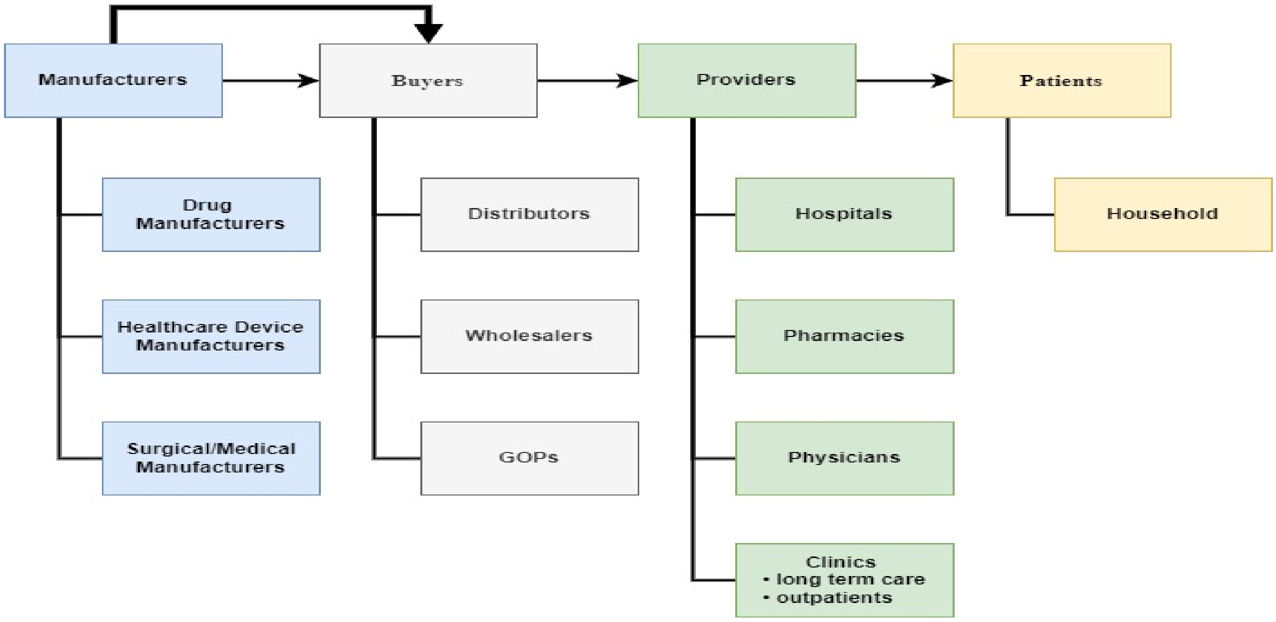

Fig 2. A comprehensive overview of healthcare SCM

(Prajapati, Kant, & Shankar, 2021) Identified enablers are prompting the performance of reverse SC. Their study findings suggest that organizational commitment, technological capacity, service quality, government policy, reverse SC cost, perceived usefulness, ease of use, and reverse SC performance are significant enablers of promoting reverse SC performance. Pettit and Beresford (2009) emphasized critical success factors for humanitarian-based SC. They identified the following CSFs: strategic planning, transportation planning, relationship with suppliers, management of resources, capacity planning, continuous improvement, HRM technology utilization, and information management. Azmat, M., Atif, M., & Kummer, S. (2019) investigated (internal and external) critical success factors significantly affecting (faith-based and non-faith-based) humanitarian organizations' supply chain. They identified six significant external CSFs: beneficiaries' religion, beneficiaries' culture, influence/restrictions of donors, policies of hosting countries/governments, supply lines' blockage and rough terrain, and limited/constrained resources. Furthermore, they identified four significant internal CSFs: a collection of information, structure of the organization, collaboration/coordination, and communication within the organization. Additionally, they also explored any significant differences among CSFs between religious and nonreligious organizations.

Wittstruck and Teuteberg (2012), and Schipper and Silvius (2021) considered KSFs for sustainable SCM. They described the following factors as critical: adoption of standards, signaling, information management, establishing ecological cycles, commitment, and mutual learning. Routroy and Pradhan (2013); Sarfraz et al. (2022b) considered thirteen KSFs for supplier development in the Indian manufacturing industry. The main factors include the long-term strategic goals, top management commitment, information sharing, supplier certification, innovation capability, external environment, supplier status, and direct involvement. Ab Talib, Abdul Hamid, and Thoo (2015) researched on the literature review survey by investigating twenty-six research papers. They identified four key enablers to SCM: top management commitment, information management, human resource management, and collaborative partnership.

Khan, Haleem, Khan, Abidi, and Al-Ahmari (2018) found that effective and efficient communication systems, employee training, well-established IT infrastructure, top management commitment, choosing suitable technology for traceability systems, halal SC awareness, customer satisfaction, coordination with suppliers, standardization, and government support key success factors to halal supply chain implementation. Yuen, Wang, Ma, Lee, and Li (2019) investigated 164 container shipping companies and identified and verified key enablers for supply chain integration using structural equation modeling. His study results found that the key enablers are relationship management, performance measurement, information management, strategic alignment, and organizational commitment. Finally, M. Waqas, Q.-l. Dong, N. Ahmad, Y. Zhu, and M. Nadeem (2018) identified the 47 most significant barriers to reverse logistics implementation in the Pakistani manufacturing industry and identified the top five factors as follows: lack of capital, limited planning, and forecasting, uncertainty related to economic issues, complexity in operations and lack of taxation knowledge on return products. Kaupa, F., & Naude, M. J. (2021-b) studied CSFs related to the SCM of necessary medicines in Malawi’s public healthcare system. The findings indicate that critical success factors include understanding different disease types and how they spread, sufficient financial resources, collaboration with involved SCM parties, and an effective system for purchasing and distribution. In another study, Kaupa, F., & Naude, M. J. (2021-a) investigated the barriers/obstacles in supplying the necessary medicines in Malawi's public healthcare system. Limited financial and human resources and a lack of collaboration among stakeholders were identified as the primary impediments to purchasing and SCM in Malawi's public healthcare system. The study's findings indicate that the identified barriers are critical impediments to achieving SCM's excellence, mainly in supplying essential medicines in Malawi's public healthcare system. The study recommends the following primary solutions for overcoming these challenges: development of human resources capacity, financial resource mobilization, and collaboration among stakeholders. Bentahar, O. (2018, January) investigated the factors that contribute to the success of the healthcare sector’s purchasing groups. The findings indicate that the critical success factors for purchasing groups are top management commitment, communication, anticipated benefits, collaboration, equitable distribution of savings, and indicators of performance and their measurements. Sánchez-Flores, R. B., Cruz-Sotelo, S. E., Ojeda-Benitez, S., & Ramírez-Barreto, M. (2020) conducted a systematic literature review on sustainable supply chain management (SSCM) to investigate its evolution in emerging economies. They considered and analyzed 56 papers published from 2010 until April 2020. Some of the covered papers are related to the healthcare sector, such as Subramanian, L., Alexiou, C., Steele, P., & Tolani, F. (2020), and Scavarda, A., Daú, G. L., Scavarda, L. F., & Korzenowski, A. L. (2019). Furthermore, Table 1 shows the summary of KSFs in the supply chain and healthcare sectors.

Interpretive Structural Modeling in SCM and healthcare sectors

(Agrawal, Wankhede,Wankhede & Nair, 2021) Applied ISM to identify the drivers that can hinder green supply chain management (GSCM) in the UAE manufacturing firms and rank them according to their significance. Mathiyazhagan, Govindan, NoorulHaq, and Geng (2013) used ISM to investigate the contextual relationship among the main barriers to GSCM implementation in India's manufacturing industry. Vivek and Kumar (2019) scrutinized GSCM enablers and constructed the contextual relationship-based model among different enablers in the field of FMCG by using ISM. Vishnu, Sridharan, and Kumar (2019) Identified and verified the risk drivers in supply chain management, formulated the mutual relationship model, and categorized the drivers according to their dependence and driving power using ISM and MICMAC techniques. Kannan, Pokharel, and Kumar (2009) used ISM and MICMAC approaches to prioritize the third-party logistics provider to choose the best 3PL Indian manufacturing industry. S. M. Ali, Arafin, Moktadir, Rahman, and Zahan (2018) explored the most critical barriers to implementing reverse logistics in the Bangladeshi computer supply chain and uncovered the interrelationship among selected variables through ISM methodology. Rane and Kirkire (2016) explored the barriers to ISM and developed the contextual relationship among identified barriers in the Indian medical device manufacturing industry. Jain and Ajmera (2018) tried to determine the mutual relationship among variables and ranked them according to their importance in ISM in India's healthcare sector. Bahari, Jafni, Ismail, Hashim, and Hussain (2018) tried developing the reciprocal relationship model among readiness factors that influence Malaysia's healthcare using ISM and MICMAC approaches. Karamat, Shurong, Ahmad, Waheed, and Mahmood (2018) attempted to identify the

Table 1. Identified KSFs in healthcare technology and supply chain management field

Studies	Field	Identified KSFs
(Prajapati et al., 2021) and Power et al. (2001)	SCM	Supplier relations, computer-based technologies, technology utilization, just-in-time methodology, resource management, continuous improvement enablers, participative management style, customer satisfaction, product innovation, and delivery performance.
(Chatterjee & Chaudhuri, 2022),Tan et al. (2002)	Customer relationship management	Customer-centric strategy, commitments from people, improved or redesigned process, software technology and infrastructure.
Gunasekaran and Ngai (2003); (Singh, Dasgupta, & Routroy, 2022)	Reverse logistics	Information technology, strategic planning, capacity planning, inventory management and transportation
Al-Mashari, Al-Mudimigh, and Zairi (2003)	Enterprise resource planning	Correspondence success, process success, interaction success, expectation success, organizational relating, IT infrastructure, Strategic relating, managerial relating and operational relating.
(Thomassey & Zeng, 2021), Ngai, Cheng, and Ho (2004)	Web-based SCM	Communication, training and education, software and hardware reliability, top management commitment, and data security

Gottschalk and Solli-Sæther (2005)	IT-based SCM	Management competency, management of stakeholders, transaction cost reduction, reduction of production cost, and contract maturity.
Rao Tummala et al. (2006)	SCM	Improving inventory, reducing the cost of operations, cross-functional communication, Creating corporate culture lead time, and customer satisfaction.
Kuei et al. (2008)	Quality management of SCM	Quality of SC leadership, relationship with suppliers, consumer focus, IT system quality, and focus on the integration process.
Hong, Suh, and Hou (2008)	Reverse SC	Organizational commitment, technology capacity, service quality, government policy, reverse SC cost, perceived usefulness, ease of use, and reverse SC performance.
Pettit and Beresford (2009)	Humanitarian SC	SC strategy, strategic planning, transportation planning, relationship with suppliers, management of resources, capacity planning, focus on continuous improvement, HRM technology utilization, and information management.
Lönngren, Rosenkranz, and Kolbe (2010)	Construction of supply chain	IT application solution, task management, and trust among partners.
(Waqas, Honggang, Ahmad, Khan, Ullah, et al., 2021), Lee, Lee, and Schniederjans (2011)	SC innovation Healthcare	SC innovation, collaboration with suppliers, supply chain efficiency, quality management practices, and firm performance.
Wittstruck and Teuteberg (2012)	SCM	Adoption of standards, signaling, information management, the establishment of ecological cycles, commitment, and mutual learning.
Routroy and Pradhan (2013)	SCM	The long-term strategic goal, top management commitment, information sharing, supplier certification, innovation capability, external environment, supplier status, and direct involvement.
Grimm, Hofstetter, and Sarkis (2014)	Supplier management	Costs, lack of capital, lack of skills, lack of top management commitment, investment reluctance, lack of power, stakeholder partnerships, lack of trust between supply chain partners, lack of information, transparency, language differences and geographical distance.
Ab Talib et al. (2015)	SCM	Top management commitment, information management, human resource management, and collaborative partnership.
Mangla, Govindan, and Luthra (2016)	Reverse logistics	HR and organizational factors, regulatory pressure, global competitiveness factors, economic considerations, and strategic factors.
(Khan, Godil, Jabbour, et al., 2021)Raut, Narkhede, and Gardas (2017)	SSCM	Global environmental pressure and scarcity of natural resource resources.
Khan et al. (2018)	Halal supply chain	Training of employees, efficient and effective communication, dedicated IT infrastructure, top management support, Selection and selection of Suitable Technology for Traceability Systems, halal awareness, customer satisfaction, coordination with

		suppliers, standardization and Codification, and government support.
Karamat et al. (2019)	Knowledge management in healthcare	Maintain green competitive advantage, setting a standard for other organizations, Effective decision making, Intra organizational communication in healthcare, and collaboration with other healthcare organizations.
Yuen et al. (2019)	Supply chain integration	relationship management, performance measurement, information management, strategic alignment, and organizational commitment.

Enablers of knowledge management implementation in the Pakistani healthcare sector using ISM-MICMAC. Sadeh and Garkaz (2019) uncovered influential quality factors in the Iranian medical tourism sector by applying ISM-MICMAC framework. Rane and Kirkire (2017) developed the interaction between risk sources and categorized them according to their dependence and driving power in the Indian medical device development sector. Furthermore, Table 2 contains more details about ISM and MICMAC approaches in SCM and healthcare sectors in different countries

Table 2. Studies used ISM in the field of healthcare and SCM

Ref.	**Field**	**Objective**
(Rane & Kirkire, 2016)	Healthcare	Exploring barriers to ISM and developing a contextual relationship among identified barriers in the Indian medical device manufacturing industry.
(Diabat & Govindan, 2011)	SCM	Identifying factors that can hinder the implementation of GSCM in UAE manufacturing firms and ranking them according to their significance by using ISM.
(Jain & Ajmera, 2018)	Healthcare	Using ISM, we identify the mutual relationship among affected medical tourism in India's healthcare sector and rank them according to their importance.
(Mathiyazhagan et al., 2013)	SCM	This study investigates the contextual relationship among the main barriers to GSCM implementation in India's manufacturing industry.
(Bahari et al., 2018)	Healthcare	It is developing the mutual relationship model among readiness factors that influence personal healthcare in Malaysia.
(Vivek & Kumar, 2019)	SCM	Scrutinized GSCM enablers and constructed the contextual relationship model among different enablers in FMCG.
(Ajmera & Jain, 2019b)	Healthcare	Evaluate and prioritize the critical factors that impact the quality of life of Indian diabetic patients by using the ISM technique.
(Vishnu et al., 2019)	SCM	Identify and verify the risk drivers in supply chain management, formulate the mutual relationship model, and categorise them according to their dependence and driving power using ISM and MICMAC techniques.

(Karamat et al., 2019)	Healthcare	Analyze the barriers and drivers to knowledge management and rank on their driving and dependence power in the Pakistani healthcare sector.
(Kannan, Pokharel, & Kumar, 2009)	Reverse logistics	ISM and MICMAC approach prioritizes the third-party logistics provider to choose the best 3PL in the Indian manufacturing industry.
(Rane & Kirkire, 2017)	Medical device development	Identify and develop the interaction between risk sources and categorize them according to their dependence and driving power in the Indian medical device development sector.
(S. M. Ali et al., 2018)	Reverse logistics	Using the ISM approach, this study explores the most critical barriers to reverse logistics in Bangladeshi computer supply chain.
(Sadeh & Garkaz, 2019)	Healthcare	This study investigates influential quality factors in Iranian medical tourism by applying ISM and MICMAC frameworks.
(Sindhwani, Mittal, Singh, Aggarwal, & Gautam, 2019)	Manufacturing systems	This study establishes an interrelationship and evaluates barriers' driving and dependence power by applying total ISM and MICMAC in the Indian manufacturing industry.
(Bouzon, Govindan, & Rodriguez, 2015)	Reverse logistics	Using ISM, we evaluate and analyze the contextual relationship among barriers to reverse logistics implementation in the Brazilian manufacturing industry.
(Ajmera & Jain, 2019a)	Healthcare	This study aims to identify the most influential factors in implementing lean principles in the Indian healthcare sector.
(Shibin et al., 2016)	GSCM	We explore barriers and enablers in flexible GSCM networks and highlight the mutual relationship among selected barriers and enablers through expert opinion by using ISM.
(Talib, Rahman, & Qureshi, 2011)	Total quality management	This study examines the barriers to TQM in the service sector and identifies the mutual relationships among selected obstacles by using the ISM methodology.
(Karamat et al., 2018)	Healthcare	To identify the enablers of knowledge management implementation in the Pakistani healthcare sector using ISM and MICMAC.
(Malviya & Kant, 2017)	SCM	This study's main objective is to identify and examine the interaction among enablers of GSCM implementation and their driving and dependence power by applying ISM and MICMAC approaches.

Research gap

Pakistan is emerging as a significant worldwide center for healthcare facilities. The Pakistani healthcare supply chain faces numerous barriers regardless of this remarkable growth. There is a need to effectively promote KSFs in the supply chain of the healthcare industry of Pakistan. However, countries across the globe face similar KSFs during the implementation of the healthcare sector's supply chain. However, the differences in industrial culture, socio-economic conditions, and rules and regulations can change each KSFs' treatment in every country. A comprehensive literature on identifying KSFs has witnessed the popularity area among scholars in various countries. More importantly, developing reliable solutions to endorse the healthcare industry's efficient and cost-effective supply chain. The earlier segments lead the current study to identify the below-given research gaps:

- There is a shortage of research evaluating KSFs in the healthcare supply chain, particularly in Pakistan.
- Pakistan seeks solutions to selected KSFs to implement a better healthcare sector's supply chain to serve patients in critical and emergency conditions cost-effectively. Identification and verification of KSFs in the supply chain are minimal due to researchers' low interest; the Pakistani healthcare supply chain faces many challenges, especially in emergencies.
- ISM and MICMAC methodology has been widely applied in diversified fields, but their application in the healthcare supply chain is minimal. According to the writer's knowledge, no earlier study has used the combination of ISM and MICMAC methodology to evaluate the KSFS in the healthcare supply chain in the Pakistani context.

METHODOLOGY

The framework of a four-stage methodology has been applied to evaluate the KSFs in healthcare SC. At the first stage, KSFs in healthcare SC were identified, which were further screened out with the Delphi method's facilitation at the second stage. ISM-based contextual relationship model was established at the third stage to intensify the understanding of the levels of hierarchal structure of KSFs. Finally, MICMAC was applied to classify and develop clusters of KSFs in healthcare SC. The main stages involved in the methodology have been shown in the dotted box, along with the substages and other activities, as shown in Figure 3.

Furthermore, the description of each stage is also explained in the following sections.

Identification of KSFs

For reviewing the literature of KSFs, this research has applied a systematic literature review (SLR) technique, as suggested by (Thürer, Tomašević, Stevenson, Qu, & Huisingh, 2018). The literature review survey was done from September 2019 to October 2019. The related research papers were collected from literature through the undermentioned criteria:

1. The research papers must contain key success factors/ critical success factors in the healthcare supply chain. Moreover, the leading keywords used for paper selection are: 'healthcare', 'supply chain', 'medical technology', 'medical tourism industry, 'KSFs', 'barriers', 'CSFs', 'obstacles'. A combination of leading keywords used for paper selection is (1) key success factors in the healthcare supply chain, (2) barriers/ obstacles in the healthcare supply chain, (3) critical success factors in the healthcare supply chain, (4) quality factors in medical sectors, (5) impeding factors in healthcare supply chain, (6) KSFs/CSFs in healthcare supply chain and developing countries.
2. The primary research databases, including Google Scholar, Springer, Scopus, Taylor & Francis, Science Direct, and Emerald Insight, were considered the primary sources of publication collection. The selected articles were evaluated in the screening process by finding the keywords in the title, abstract, and text to find the relevant research papers. In the process, the forward & backward snowball research

technique was also applied to screened articles, as suggested by (Danglot et al., 2019). However, another criterion, "inclusion/exclusion applied to refine the research articles more appropriately described as (i) published articles written in the English language, (ii) peer-reviewed research articles, proceedings of the conference, and chapters published in books were considered.

3. The criteria mentioned above helped select the relevant research articles for this study; the chosen articles contained the literature related to KSFs/CSFs, barriers, challenges, and obstacles to the healthcare supply chain. The Main KSFs in the healthcare supply chain has been given in Table 2.

The different leading journals belonging to this study were the primary source for finding relevant published articles are *production planning & control, environmental research and public health, international Journal of healthcare management, international journal of physical distribution & logistics management, Journal of cleaner production, Journal of environmental management and renewable, sustainable energy review and Journal of business & industrial marketing.*

Questionnaire formation and data collection

The nature of this study is empirical, and previous studies found KSFs in developed countries. The lack of KSFs studies in Pakistani literature and selecting the most appropriate experts for this study was problematic. Therefore, pilot testing was applied to choose the proper respondents. The experts from the field were approached through text messages, phone calls, and emails and arranged an appointment in office for inquire their willingness to participate. Finally, six experts with an excellent background in the supply chain were engaged in this study for data collection, and semistructured interviews were performed. The respondents include: 1) two professors of SCM, 3) one production manager, 4) one procurement manager, 5) one transportation manager, and 6) data analyst. All participants had comprehensive knowledge about SCM and were well aware of the selected KSFs in the healthcare supply chain. The following questions were asked by the participants in a group discussion:

Q1. What are the key success factors for a manufacturer in the healthcare supply chain? (Content confirmation from Table 1)

Q2. What are the most related KSFs to the healthcare supply chain of Pakistan?

Q3. What is the contextual relationship among different KSFs in the healthcare supply chain? (ISM & MICMAC)

A comprehensive questionnaire was designed on behalf of experts' responses about the importance of each KSFs. Through a qualitative technique, all selected KSFs were evaluated manually. All expected relationships among selected KSFs were discussed in a group discussion with experts. Each expert's response was registered to the structural self-interaction matrix (SSIM) and then converted into ISM based contextual relationship model. Furthermore, the ISM methodology is elaborated in detail:

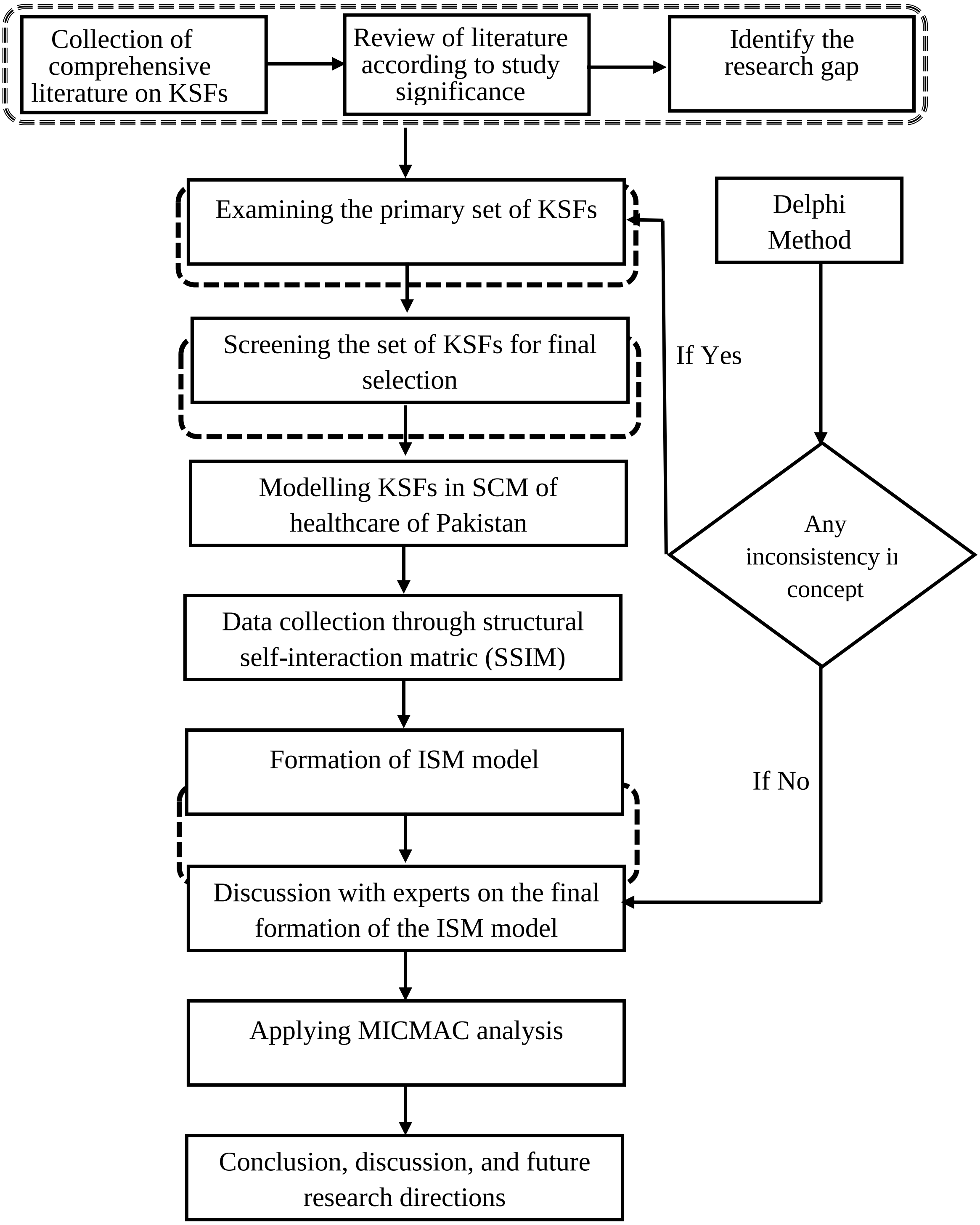

Fig 3. Step by step framework of the study

Interpretive structural modeling (ISM)

Interpretive structural modelling is considered an advanced Multiple-Criteria Decision-Making (MCDM) methodology to examine the relationship among different factors in a complex situation through professional judgment (Warfield & Cybernetics, 1974). ISM analyzed the selected elements in the system to identify a causal interrelationship graph. Furthermore, many characteristics of ISM methodology that verify its appropriateness to apply in this study are as follows:

- ISM enables experts to tap into complex systems factors through practical knowledge and judgment and create an understandable and comprehensive model.
- Complex relationships among different factors can be calculated in a logical order.
- ISM methodology is extensively applied by social science and supply chain management scientists and has also been used by some admired institutions such as NASA (Ansari et al., 2013).
- Since its introduction, it has been widely applied to evaluate the complex system's cause-and-effect associations between selected elements/variables. In this paper, KSFs in the healthcare supply chain are considered as factors.
- It's a beauty of ISM methodology, it doesn't need the earlier background of a system and ranks each factor according to its significance.

However, some drawbacks are also affiliated with ISM methodology, such as the contextual relationship ISM model depends upon the practical knowledge and judgments of professionals relevant to the system. Thus, wrong perceptions or inconsistent professionals' understanding of factors might affect the study's findings. According to (Ansari et al., 2013), ISM is not proficient enough to calculate the associated factors' accurate weights. In this case, the ISM methodology is appropriate for the current study because of its advantages. Identifying KSFs in the healthcare supply chain is a complex issue, and experts' participation is more suitable in this background because of their practical knowledge and experience. In these kinds of situations, data collection from stakeholders regarding the identification of KSFs is uncertain because of respondents' limited ability. However, a broad literature on ISM methodology is presented in Table 2, which confirms its suitability to resolve complex problems in different fields.

The ISM methodology application presents the structural transparency and introduces the hierarchical model to identify the contextual association among selected factors. The steps involved in the ISM methodology are given below:

Step 1: According to the Pakistani context, KSFs in the healthcare supply chain are identified through extensive literature review and filtered through professionals' suggestions.

Step 2: In the first step, the contextual relationship among the selected KSFs was established to confirm which pair of KSFs was studied in the next step.

Step 3: Step three shows the pairwise relationships among selected KSFs through a developed SSIM.

Step 4: From SSIM, an initial reachability matrix (IRM) was identified, and later IRM is examined for transitivity, which is considered a basic assumption of ISM methodology. It defines that if a KSF "A" is associated with "B" and "B" is associated with "C," then "A" must be related to "C."

Step5: With the help of an initial reachability matrix, various iterations were achieved to get the ISM model's level.

Step 7: Finally, the diagram is shaped into an ISM model by replacing KSFs nodes with statements.

Step 8: To improve the ISM model, the model's conceptual inconsistency was rechecked for further modifications, if necessary.

Development of structural self-interaction matrix (SSIM)

In ISM methodology, experts in the field are the primary source to judge the directional relationship between two selected KSFs (i and j). Four symbols identify the directional relationship between selected factors (i and j).

- V: KSFs “i” will help to achieve KSFs “j”
- A: KSFs “j” will help to achieve KSFs “i”
- X: KSFs “i” and “j” will help to achieve each other
- O: KSFs “i” and “j” are not related

According to their best knowledge, the symbols (V, A, X, O) were assigned to each KSFs by experts, as shown in Table 3.

Initial reachability matrix (IRM)

The initial reachability matrix is obtained from the structural self-interaction matrix at this stage. In Table 4, the symbols (V, A, X, O) are translated into a binary matrix (i.e., 0 or 1), an initial reachability matrix. The following translation rules are applied:

If (i and j) cell presents the symbol “V” in SSIM, then 1 will be allotted to (i and j) cell, and 0 will be assigned to (j and i) cell in the initial reachability matrix.

If (i and j) cell presents a symbol “A” in SSIM, then 0 can be allotted to (i and j) cell, and 1 can be assigned to (j and i) cell in the initial reachability matrix.

If (i and j) cell presents a symbol “X” in SSIM, then 1 be allotted to both cells (i and j) and (j and i) in the initial reachability matrix.

If (i and j) cell presents the symbol “O” in SSIM, then 0 will allot to both cells (i and j) and (j and i) in the initial reachability matrix.

The results for IRM are further presented in Table 4.

Final reachability matrix

The IRM for KSFs in the Pakistani healthcare supply chain was obtained from SSIM. Furthermore, by removing the transitivity of IRM, as mentioned in step 4, the final reachability matrix (FRM) was derived and presented in Table 5. However, the dependence and driving power of each selected KSFs have been derived from FRM.

Partitions level

FRM is employed to drive the reliability and antecedent sets of each selected KSFs, as suggested by Warfield and Cybernetics (1974). According to Ahmad, Zhu, Hongli, et al. (2019), the reachability set contains the factor (KSFs) itself and its supporting factors that may help to attain. In contrast, the antecedent set contains the factor (KSFs) itself and other factors that may influence achieving it. Further, the intersection set encompasses all those values included in reachability and antecedent sets. If the reachability set and intersection set contain the same values, it achieves the first level. The same procedure is continued until the achievement of all levels of each KSFs, presented in Table 6. The following identified levels help to construct the ISM-based contextual relationship-based model.

Table 6 shows the lack of initial capital identified as the main KSF in the Pakistani healthcare supply chain, which leads to other selected factors.

Formation of the ISM model

A structural model is constructed from FRM, as presented in Figure 4. Arrows beginning from KSFs i to KSFs j portray the contextual relationship among selected KSFs. The initially formulated diagram is named as diagraph. After eliminating transitivity, the diagraph is converted into an ISM based model for KSFs in the healthcare supply chain, as presented in Figure 5. Furthermore, the MICMAC approach was applied to identify the four clusters of selected KSFs in the Pakistani healthcare supply chain.

MICMAC analysis

According to Waqas, Qianli, Ahmad, Zhu, and Nadeem (2020), MICMAC is an abbreviation for (Matriced' Impacts croises-multipication applique' an classment), (cross-impact matrix multiplication applied to classification). MICMAC research methodology was used to explore more profound insights of selected KSFs in the Pakistani context. MICMAC analysis's key objective was to determine the impact of each KSFs in the healthcare supply chain for their better implementation. However, conferring on the driving and dependence power of each selected KSFs, they have been divided into four groups: autonomous KSFs, linkage KSFs, dependent KSFs and independent KSFs (Govindan, Palaniappan, Zhu, & Kannan, 2012).

However, based on ISM and MICMAC analysis results, the final output of the ISM analysis is shown in Figure 4, which further derives the ISM model (as shown in Figure 5). Lastly, the final findings of the MICMAC approach are presented in Figure 6.

At this stage, clustering for KSFs was done using the MICMAC technique. The driving and dependence power of each KSFs was used. According to the driving and dependence power of each selected KSFs, they have been divided into four groups: autonomous KSFs, linkage KSFs, dependent KSFs, and independent KSFs (Govindan et al., 2012; Kannan, Pokharel, Kumar, & recycling, 2009). Results of four clusters of KSFs by following the rules of MICMAC are described below:

Autonomous KSFs

KSFs with weak driving and dependence power are placed in this Quadrant. These factors are often disconnected from others and may have little links with other factors, but their links can be strong in effect. Quadrant I is presenting autonomous KSFS. In this study, no KSFs were identified in this quadrant, which means that all selected KSFs are more significant to the healthcare supply chain in the Pakistani context.

Dependent KSFs

KSFs with weak driving, but strong dependence power is placed in this Quadrant. These kinds of factors are considered ineffective in attaining other factors. Quadrant-II presents dependent KSFs. In this study, three KSFs named relationship with customers (9RC), transport management (11TM), and sales and production planning (17SA) were identified in quadrant-II.

Linkage KSFs

KSFs with strong dependence and driving power are placed in this Quadrant. These factors are susceptible and unstable because any action taken on them will impact the whole system. Quadrant III presents linkage KSFs. In this study, fifteen KSFs were named, top management commitment (1CT), skilled professionals, SCM (4SP), teamwork (15TW), organizational support (16OS), insufficient strategic planning (18IS), conflict among employees (20CE), reverse logistics infrastructure (10RL), green supply chain management (12GS), resistance to change (19RC), new technology and information systems (3NT), strategic partnership with suppliers (7SS), information quality (5IQ), quality and safety compliance (14QS), inventory management (6IM) and distribution system (13DS) were identified in linkage quadrant according to their driving and dependence power.

Independent KSFs

KSFs with strong driving but weak dependence power are placed in this Quadrant. A KSFs having strong driving power was identified as the study's main factor and placed independent KSFs quadrants. Quadrant IV is presenting driving KSFs. In this study, two KSFs named initial capital (2IC) having driving power 20, dependence power 2, and training & experience (8TE) having driving power 19, dependence power 8, respectively, were identified in quadrant IV. Table 5 presents the driving and dependence power of each selected KSFs. Further detail relating to the formation of the MICMAC analysis model can be seen in Figure 6.

Table 3. Structural self-interaction matrix for KSFs

Codes	KSFs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1CT	Top management commitment		A	V	V	V	V	V	V	O	V	V	V	V	V	V	V	O	A	V	O
2IC	Initial capital			V	V	V	O	O	V	O	V	V	V	V	V	O	V	V	V	O	O
3NT	New technology and information systems (NTIS)				A	V	V	A	O	O	V	V	V	V	V	V	O	O	O	O	O
4SP	Skilled professionals in SCM					V	V	V	V	V	V	V	V	V	V	X	V	V	V	O	V
5IQ	Information quality						V	O	A	O	A	O	O	V	V	O	V	V	V	V	V
6IM	Inventory management							O	A	O	A	O	A	X	A	O	V	V	A	O	O
7SS	Strategic partnership with suppliers								A	O	A	O	A	V	V	O	V	V	A	A	O
8TE	Training & experience									V	V	V	O	O	V	V	V	V	O	V	V
9RC	Relationship with customers										O	O	A	O	O	O	O	O	O	O	O
10RL	Reverse logistics infrastructure											V	A	V	V	V	A	V	A	A	O
11TM	Transport management												A	X	A	O	A	O	A	O	O
12GS	Green supply chain management (GSCM)													V	V	O	A	V	A	O	O
13DS	Distribution system														A	A	A	V	O	O	O
14QS	Quality and safety compliance															A	A	O	A	O	A
15TW	Team work																X	V	X	O	X
16OS	Organizational support																	V	V	V	V
17SA	Sales and production planning																		A	O	O
18IS	Insufficient strategic planning																			V	V
19RC	Resistance to change																				V
20CE	Conflict among employees																				

*Based on experts' response

Table 4. Initial reachability matrix for KSFs

No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	1	0
2	1	1	1	1	1	0	0	1	0	1	1	1	1	1	0	1	1	1	0	0
3	0	0	1	0	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	0
4	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
5	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	1	1	1	1	1
6	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0
7	0	0	1	0	0	0	1	0	0	0	0	0	1	1	0	1	1	0	0	0
8	0	0	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	0	1	1
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	1	1	1	0	0	1	1	0	1	1	1	0	1	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
12	0	0	0	0	0	1	1	0	1	1	1	1	1	1	0	0	1	0	0	0
13	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	1	0	0	0
14	0	0	0	0	0	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0
15	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1
16	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
18	1	0	0	0	0	1	1	0	0	1	1	1	0	1	1	0	1	1	1	1
19	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1
20	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1

Table 5. Final reachability matrix for KSFs

No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Dri.
1	1	0	1	1	1	1	1	1	1*	1	1	1	1	1	1	1	1*	1*	1	1*	19
2	1	1	1	1	1	1*	1*	1	1*	1	1	1	1	1	1*	1	1	1	1*	1*	20
3	0	0	1	1*	1	1	1*	0	1*	1	1	1	1	1	1	1*	1*	1*	1*	1*	17
4	1*	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1*	1	19
5	1*	0	0	1*	1	1	1*	0	0	1*	1*	1*	1	1	1*	1	1	1	1	1	16
6	0	0	0	0	0	1	0	0	0	1*	1*	1*	1	1*	1*	1	1	1*	1*	1*	12
7	0	0	1	1*	1*	1*	1	0	1*	1*	1*	1*	1	1	1*	1	1	1*	1*	1*	17
8	1*	0	1*	1*	1	1	1	1	1	1	1	1*	1*	1	1	1	1	1*	1	1	19
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
10	1*	0	1*	1*	1	1	1	0	1*	1	1	1*	1	1	1	1*	1	1*	1*	1*	18
11	0	0	0	0	0	1*	0	0	0	0	1	0	1	0	0	0	1*	0	0	0	4
12	1*	0	1*	1*	1*	1	1	0	1	1	1	1	1	1	1*	1*	1	1*	1*	1*	18
13	0	0	0	0	0	1	0	0	0	1*	1	1*	1	1*	1*	1*	1	1*	1*	1*	12
14	0	0	0	0	0	1	0	0	0	1*	1	1*	1	1	1*	1*	1*	1*	1*	1*	12
15	1*	0	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1	1	1	1	1*	1	19
16	1*	0	1*	1*	1*	1*	1*	1*	1*	1	1	1	1	1	1	1	1	1	1	1	19
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
18	1	0	1*	1*	1*	1	1	1*	1*	1	1	1	1*	1	1	1*	1	1	1	1	19
19	1*	0	1*	1*	1*	1*	1	0	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1	1	18
20	1*	0	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1*	1	19
Dep.	12	1	13	14	14	18	14	8	14	17	18	17	18	17	17	17	19	17	17	17	299

Table 6. Level of partition, iterations of KSFs in healthcare supply chain

KSFs	Reachability set	Antecedent set	Interaction set	Level
1	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	1,2,4,5,8,10,12,15,16,18,19,20	1,4,5,8,10,12,15,16,18,19,20	VI
2	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	2	2	VII
3	3,4,5,6,7,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,7,8,10,12,15,16,18,19,20	3,4,7,10,12,15,16,18,19,20	V
4	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,7,8,10,12,15,16,18,19,20	1,3,4,5,7,8,10,12,15,16,18,19,20	III
5	1,4,5,6,7,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,7,8,10,12,15,16,18,19,20	1,4,5,7,10,12,15,16,18,19,20	IV
6	6,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,11,12,13,14,15,16,18,19,20	6,10,11,12,13,14,15,16,18,19,20	1
7	3,4,5,6,7,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,7,8,10,12,15,16,18,19,20	3,4,5,7,10,12,15,16,18,19,20	IV
8	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	1,2,4,8,15,16,18,20	1,4,8,15,16,18,20	VI
9	9	1,2,3,4,7,8,9,10,12,15,16,18,19,20	9	1
10	1,3,4,5,6,7,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	1,3,4,5,6,7,10,12,13,14,15,16,18,19,20	III
11	6,11,13,17	1,2,3,4,5,6,7,8,10,11,12,13,14,15,16,18,19,20	6,11,13,	II
12	1,3,4,5,6,7,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	1,3,4,5,6,7,10,12,13,14,15,16,18,19,29	III
13	6,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,11,12,13,14,15,16,18,19,20	6,10,12,13,14,15,16,18,19,20	II
14	6,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	6,10,12,13,14,15,16,18,19,20	III
15	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	1,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	III
16	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	1,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	III
17	17	1,2,3,4,5,6,7,8,10,11,12,13,14,15,16,17,18,19,20	17	1
18	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	1,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	III
19	1,3,4,5,6,7,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	1,3,4,5,6,7,10,12,13,14,15,16,18,19,20	III
20	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20	1,2,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	1,3,4,5,6,7,8,10,12,13,14,15,16,18,19,20	III

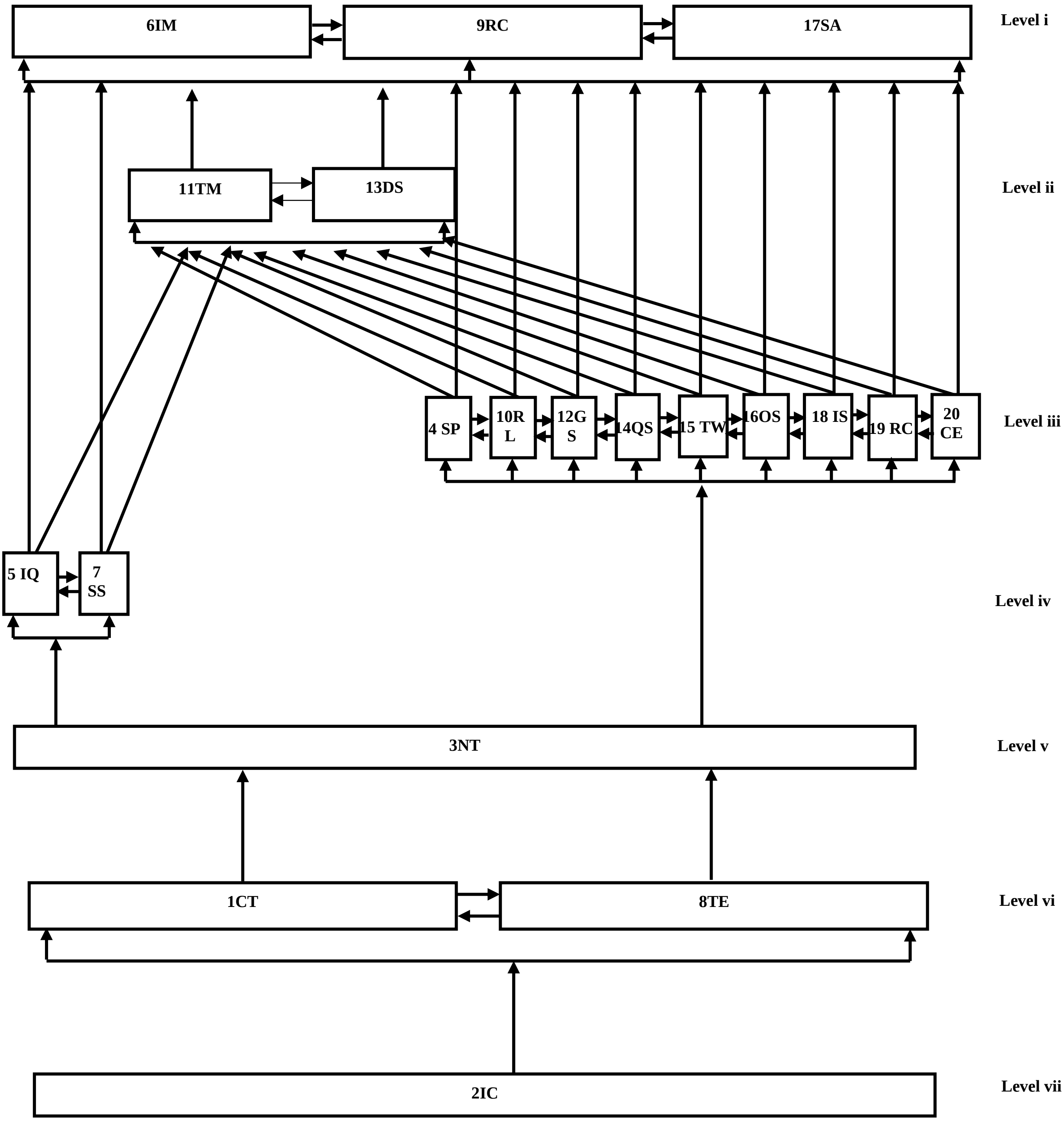

Fig 4. Diagraph of selected KSFs

RESULTS AND DISCUSSION

For an effective healthcare supply chain, focusing KSFs is unavoidable. Identify their importance in minimizing or overcoming their impact on the healthcare supply chain in the Pakistani context. This research's main objective is to identify key success factors in the healthcare supply chain for the successful implementation of supply chain operations during the shipment of healthcare products, further investigating the contextual relationship among selected KSFs. This study suggested applying ISM and MICMAC's hybrid methodology to evaluate the KSFs in the healthcare supply chain. However, successful supply chain operations in the healthcare sector are challenging without screening the severity of selected KSFs in the healthcare supply chain. This is the initial study that evaluates the KSFs in the Pakistani context's healthcare supply chain according to the literature. In the beginning, KSFs were obtained from the literature, and the final selection of KSFs was made on behalf of professionals' opinions. Then the selected KSFs were examined, and the ISM-based contextual relationship model was formulated according to the study findings.

Furthermore, the ISM based model and MICMAC results have been discussed in three sections. Firstly, the study's hierarchical structure, secondly, the top five KSFs of the study were compared with initially published studies; and thirdly, the four main quadrants of the MICMIC analysis were discussed.

Hierarchal structure

ISM methodology results derived seven levels of hierarchal structure of selected KSFs in the Pakistani context's healthcare supply chain. According to the ISM-based model, the first level extracted one KSF 'lack of initial capital (2CE)', which is identified as the most critical KSF. It means that the financial crisis is the main impediment to successfully implementing supply chain operations in the healthcare sector. Thus, the current situation can be improved by collaborating intensely with the government and different financial institutions. However, most of the authors raised the same issue in developing economies (M. Waqas, Q.-l. Dong, N. Ahmad, Y. Zhu, & M. J. S. Nadeem, 2018). First level KSFs 2CE leads 2nd level KSFs, including top management commitment (1CT) and lack of training & experience (8TE). These results were matched with an earlier study (Tumpa et al., 2019) and (Khan, Zkik, Belhadi, & Kamble, 2021), which revealed that lack of top management commitment is the most critical barrier to the adoption of GSCM in the Bangladesh textile industry. Jayant and Azhar (2014) indicated a lack of training courses as 2nd level impediment to implementing the supply chain in the Indian manufacturing industry.

New technology and information systems (3NT) were discovered at 3rd level KSFs, led by 2nd level KSFs. Appropriate technology and effective information systems play an essential role in on-time product delivery in any sector, especially in healthcare. 3NT KSF can be overcome by importing new technology and creative collaboration with developed countries. It would improve technical skills through the transformation of technical knowledge. Information quality (5IQ) and strategic partnership with the supplier (7SS) were extracted at the 4th level and were triggered by 3rd level KSFs. According to Prajapati, Kant, and Shankar (2019), information systems' inefficiency and lack of collaboration with suppliers are critical KSFs in a complex supply chain. The complexity of an information system's supply chain and inefficiencies can be removed through expertise and knowledge. The 4th level KSFs led 5th level KSFs, including nine KSFs, skilled professionals in SCM (4SP), reverse logistics infrastructure (10RL), green supply chain management (12GS), quality and safety compliance (14QS), teamwork (15TW), organizational support (16OS), insufficient strategic planning (18IS), resistance to change (19RC) and conflict among employees (20CE). These nine KSFs were identified at the 5th iteration leading 6th level KSFs, including transport management (11TM) and distribution system (13DS). Finally, two KSFs, 11 TM and 13DS, were identified at the 6th level, leading three KSFs at the 7th level, including inventory management (6IM), relationship with customers (9RC), and sales and production planning (17SA).

POLICY RECOMMENDATION AND RESEARCH IMPLICATIONS

Policy recommendations to facilitate selected KSFs in the healthcare supply chain in the Pakistani context and study implications are discussed in this segment.

Policy recommendation to facilitate KSFs in healthcare supply

Selected KSFs were divided into four categories: financial, managerial & experience, infrastructural & technological constraints, and policy factors. This segment presents the policies and implications to facilitate selected KSFs in the Pakistani healthcare supply chain.

1st level KSFs: Initial capital was identified as the most critical KSF related to financial factors and had a deep root cause for the failure of Pakistan's healthcare supply chain. However, according to the literature review, financial constraints are also faced by other developing countries such as China, India, and Bangladesh (Abdulrahman, Gunasekaran, & Subramanian, 2014; Tumpa et al., 2019). Thus, this critical KSF can be overcome by introducing short-term and long-term loans at easy terms and conditions by both government and financial institutions, e.g., the government of Pakistan has introduced the "Kamyab Jawan entrepreneurship loan scheme" for the youngster to promote small and medium businesses in the country.

2nd level KSFs: Top management commitment and training & experience related to managerial constraints were identified as the 2nd most critical KSFs to the healthcare supply chain in the Pakistani context. Less experience and lack of top management commitment may be more essential KSFs for supply chain and logistics companies, it can be overcome by logistics firms themselves by hiring skilled and professional employees, and a quarterly base training program might be introduced to enhance employee performance. Moreover, collaboration with other developing countries could improve technical skills by transforming technical knowledge.

Level KSFs: One KSFs was found at the 3rd level in the ISM model named "new technology and information system" related to infrastructural & technological constraints, hindering the operations of the healthcare supply chain. The results recommend that successful supply chain processes require new technology with a perfect information system and a skilled workforce. Thus, these actions will significantly affect the supply chain and logistics firm performance in Pakistan's healthcare sector.

4th level KSFs: Two KSFs were found at this level named “information quality and strategic partnership with supplies.” Poor information quality is another crucial KSF in supply chain and logistics because the proper product delivery at the right time depends on the information quality. Therefore, an experienced workforce is considered the basic fundamental for controlling and conveying the correct information at the right time in supply chain and logistics firms. Lack of strategic partnership with suppliers because of the complex supply chain is also considered a crucial KSF; however, previous studies opposed this idea. In the Pakistani context, supply chain and logistics departments are failed to improve performance, especially in the healthcare sector. The main reason behind this is the lack of coordination with their partners. It also leads to falling in sustainable long-run relationships with their suppliers, and suppliers are hesitant about coordinating with them.

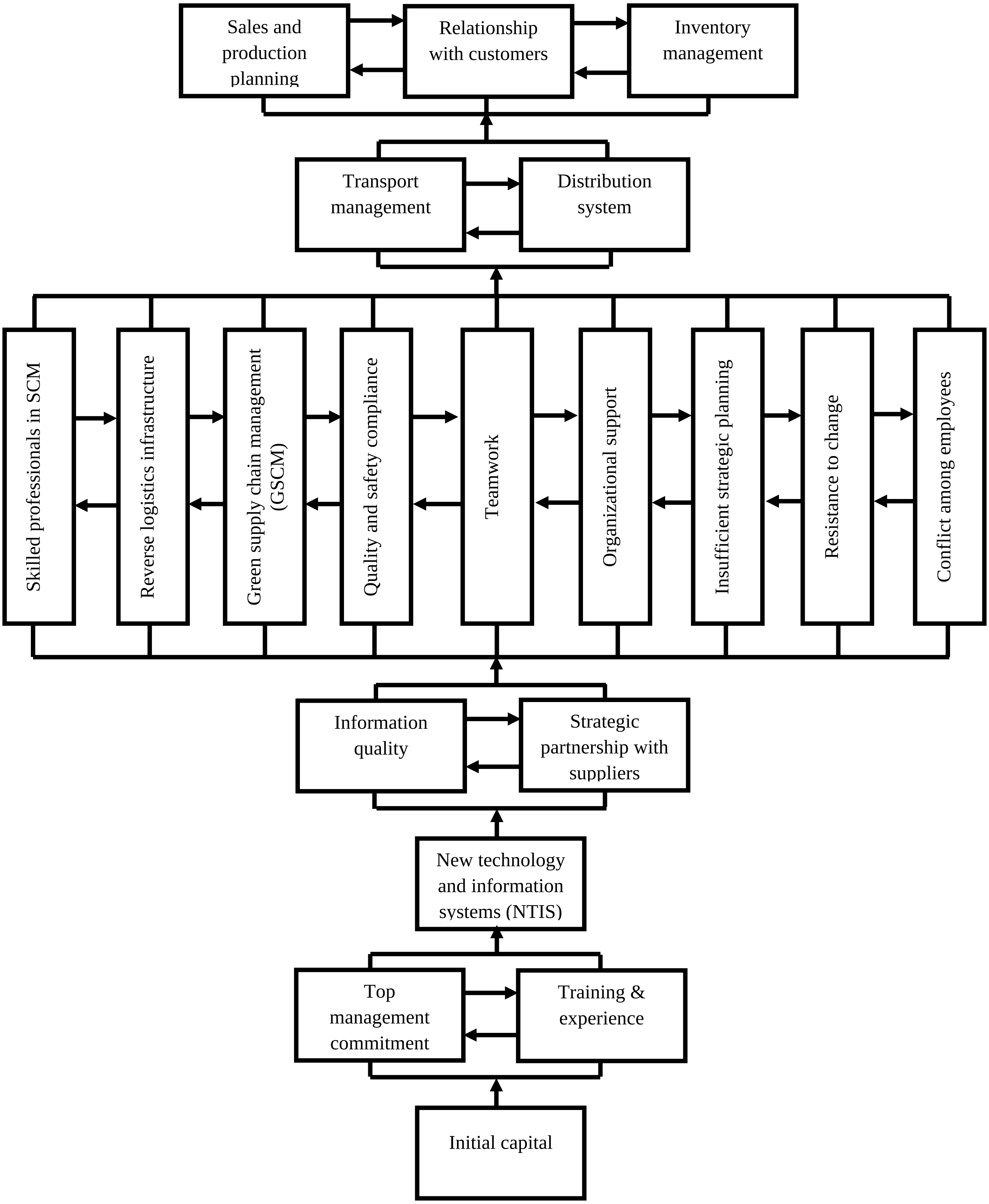

Fig 5. ISM based model for selected KSFs in healthcare supply chain of Pakistan

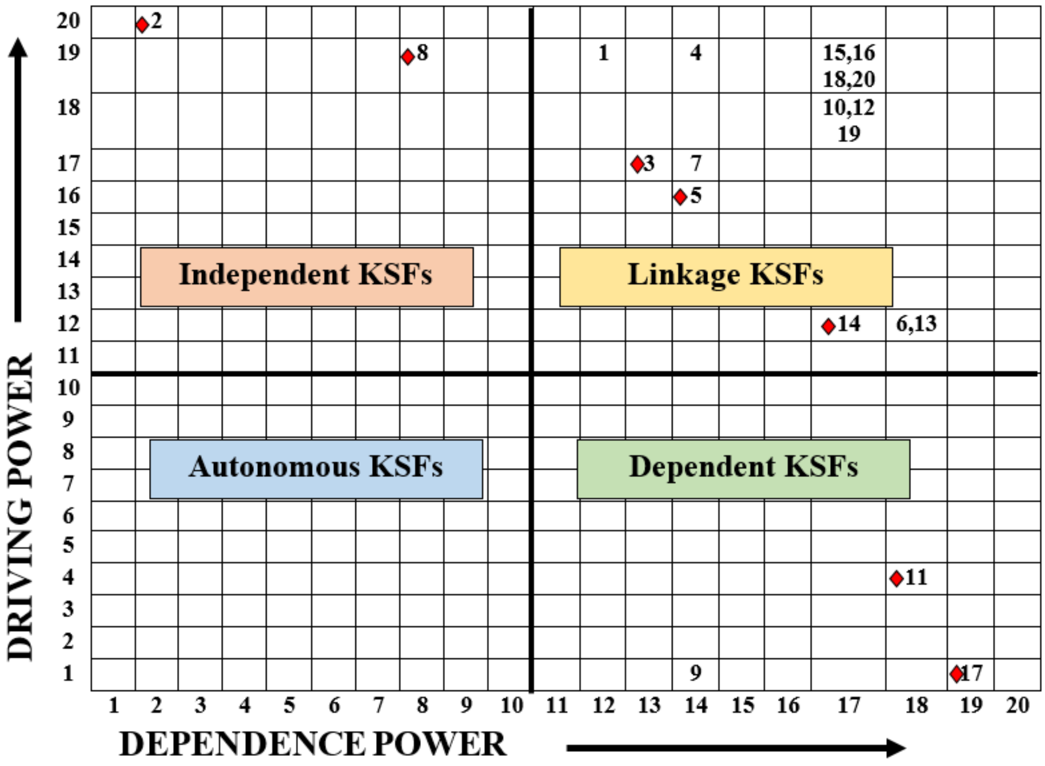

Fig 6. MICMAC analysis-based model for selected KSFs in the healthcare supply chain of Pakistan

5th level KSFs: Most of the selected KSFs were found at the 5th level named: skilled professionals in SCM, reverse logistics infrastructure, green supply chain management, quality and safety compliance, teamwork, organizational support, insufficient strategic planning, resistance to change, and conflict among employees. Skilled professionals assist firms in gaining a good position, but on the other hand, a less experienced workforce is a significant hindrance to adopting new technology in any sector. The study finding suggests that supply chain and logistics firms require skilled professionals to successfully implement the operations supply chain. Moreover, reverse logistics infrastructure is also needed to make supply chain operations cleaner and greener. Arranging and managing training sessions and workshops might be more helpful to the productive use of new technology (Rehman Khan et al., 2021). Moreover, introducing a reward system and a supportive work environment might motivate the workforce to reduce their resistance to change during new policies and technologies (Khan, Godil, Quddoos et al., 2021).

6th level KSFs: Two KSFs were identified at this level named: transportation management and distribution system. Both KSFs are related to infrastructural & technological constraints. Our study results suggest that infrastructural & technological constraints need to overcome transportation as the leading and most important pillar in the logistics and supply chain sectors. The modernized transport system needs the Pakistani supply chain industry to manage organizational operations effectively.

7th level KSFs: Finally, three KSFs were found at this level, including sales and production planning, relationships with customers, and inventory management that belong to managerial and policy constraints. Above mentioned, three KSFs are identified as 7th level constraining factors in the healthcare supply chain of Pakistan. These can be eradicated by comparing the available budget with the company's current forecast plan and aligning the information system among production, planning, sales, supply chain, and logistics departments to obtain the set production and sales target standards. Generally, company forecasting helps avoid extra production, decreases the burden of unsold products, and increases the chances of on-time product delivery to end-users. Sustaining a solid relationship with end-users is a forward step toward producing products according to end-user expectations, which might help avoid this KSF. Inventory and data management software and a skilled operating workforce using this software might help reduce the intensity of identified KSFs at the current level.

Study implications

Considering all experts' opinions, the current study results disclose that the first three levels of KSFs are identified as critical to the health care supply chain. It shows that healthcare firms in different developing countries face diverse KSFs because of economic, social, and political changes. Therefore, this also reveals that the same strategies dealing with KSFs of logistics and supply chain firms may not deliver the required results for the up-gradation of the whole industry. Solutions on promote KSFs to the healthcare supply chain might be different from firm to firm as well as country to country. However, the identified KSFs in the Pakistani context of the healthcare supply chain is limited in the literature review.

Most of the literature studies have evaluated different KSFs impeding supply chain and logistics services in the healthcare sector in developed countries; however, very few research papers are found on the identification of KSFs in developing countries' contexts. Moreover, very little research in literature identifies the contextual relationship among different supply chain KSFs, but no study is found in the Pakistani context. Application of ISM and MICMAC analysis is common in very renowned fields such as construction, manufacturing, management, and marketing. However, its application in the healthcare supply chain, especially in Pakistan is limited. However, this research adds to the literature theoretically by applying the combination of a new methodology of ISM and MICMAC in the healthcare supply chain in the Pakistani context. Considering the results, this study reveals different managerial and practical implications.

An ISM-based model guides how these selected KSFs can be correlated, and the ISM model also unveils their contextual relationship. Lack of initial capital has been identified as the most critical barrier and has deepened the root for other selected KSFs in an ISM model. Government agencies and financial institutions can overcome financial constraints in the healthcare supply chain. Furthermore, China aims to invest 46 billion dollars in different projects under the China Pakistan Economic Corridor (CPEC) umbrella. The Pakistani supply chain and logistics sector and the government should highlight this sector's potential to attract Chinese private and state-owned supply chain and logistics companies to invest in this sector. Lack of initial capital leads to a lack of top management commitment and training & experience that are identified as 2nd level KSFs. The untrained workforce issues can be resolved by learning from China's expertise because China has one of the world's advanced supply chain and logistics infrastructures and an experienced workforce. This research will be confidently helpful in resolving the most critical KSFs of the healthcare supply chain efficiently and effectively in the Pakistani context. The results of this research might also be beneficial for other developing countries such as India, Bangladesh, and Iran. Furthermore, this study's findings might also help simplify the adoption of green supply chain management processes in the Pakistani manufacturing industry to accomplish sustainable development goals (SDG) related to healthcare (Khan, Mathew, Dominic, & Umar, 2021).

CONCLUDING REMARKS

The healthcare products manufacturing industry is one of the high-pressure industries to manufacture and deliver those products that give patients relief in their critical situations. The Drug Regulatory Authority of Pakistan (DRAP) ensures that the drug manufacturing companies are producing their products under current medical laws. The fear of fake medicines, product quality concerns, security and traceability, and authorized healthcare products in this sector. Manufacturers are now requested to deliver documented proof that the returned product has been manufactured under quality standards; in the case of negligence, all delivered products can be recalled from the markets, thus demanding supply chain and logistics efficiency. Considering the current situation, this research aimed to identify KSFs to the healthcare supply chain in the Pakistani context and formulate a contextual relationship-based model that uncovers hidden interactions among selected KSFs.

Twenty main KSFs were selected from the literature and experts' opinions on the healthcare supply chain and logistics in the Pakistani context. Sales and production planning, relationships with customers and inventory management are identified as top-level KSFs in the ISM model driven by its next-level KSFs. Transportation management and distribution systems were situated at the 2nd level of the ISM model. The 3rd level includes skilled professionals in SCM, reverse logistics infrastructure, green supply chain management, quality and safety, compliance, teamwork, organizational support, insufficient strategic planning, resistance to change, and conflict among employees. Information quality and strategic partnerships with suppliers were identified as the 4th level. New technology and information systems were located at the 5th level. The 6th level contains a top management commitment and training and experience.

Lack of initial capital is identified as the most critical KSFs to the healthcare supply chain in Pakistan. It presents intense driving but weak dependence power and is located at the base of the ISM model. It is concluded that the lack of initial capital is the primary failure of supply chain and logistics firms in Pakistan's healthcare sector. In fact, according to the current situation, a shortage of financial resources exists in every industry in Pakistan, so this study makes the point valid. An ISM and MICMAC analysis revealed the hierarchical structure of selected KSFs in the Pakistani context to overcome or reduce their intensity in the logistics and supply chain. This study's findings can help concerned authorities better understand critical KSFs on a priority basis, and more severe KSFs can be dealt with according to their severity. This research has some limitations. In the current study, ISM Model was formulated with twenty KSFs in the healthcare supply chain, selected through extensive literature and finalized with experts' opinions according to the Pakistani context. According to their country context, future research may focus on other critical KSFs in the supply chain. However, this study's results might benefit developing countries with similar economic conditions. The current study's findings can be verified and analyzed using the Structural Equation Modeling (SEM) methodology. Furthermore, the significance of selected KSFs can also be evaluated by a structural model in the healthcare supply chain. The current study's findings can be further examined in the near future by applying research techniques such as the analytic hierarchy process (AHP), analytic network process (ANP), DEMATEL, and fuzzy methods.

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ORIGINAL PAPER

BARRIERS TO ELECTRONIC DATA EXCHANGE IN THE SUPPLY CHAIN - RESULTS FROM EMPIRICAL STUDY

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ABSTRACT. Background: The purpose of this article is to present the results of a study on barriers to data exchange in supply chains between logistics service providers (3PL and 4PL) and their customers in Poland. The study investigates two research hypotheses regarding the relationships between the size of a company and the role of a logistics service provider in the electronic data exchange between their business partners.
Methodology: Bayesian ordinal regression was used to assess the reliability of the research hypotheses. The study used survey data from a population of 78 logistics service providers operating in Poland. Feedback was received from 51 respondents. Originality of the presented research results from the applied research method, Bayesian ordinal regression, rarely used in economic sciences to assess the reliability of research hypotheses concerning the determination of determinants of the studied phenomenon. The defined research hypotheses represent an important contribution to the research on communication in supply chains.
Results: The results indicate that the level of the employment and the role of logistics service provider in a supply chain do not determine the extent of problems in electronic communication between the logistics operator and customers.

Keywords: EDI, logistics provider, supply chain

INTRODUCTION

Today, the amount of data generated by companies is increasing dramatically every year [Krajk et al., 2022]. More and more processes are being digitized, forcing the use of ever newer techniques [Golinska-Dawson et al., 2023]. With the increasing amount of data, companies face the problem of ensuring easy access and security of the data [Krajk et al., 2022].

The interchange of all data and information with as little human involvement as possible is the main assumption of the digital economy [Godziewska-Nowicka and Janicki, 2019]. This allows the time of information and data interchange to be reduced and reducing its cost [Combe, 2006]. The most important characteristic of digital technologies is their ability to react dynamically (fast) to sudden changes in the market and customer preferences [Szopa and Cyplik, 2020]. They also provide the opportunity to keep interactive contact with the main business partners [Wang et al., 2007].

Supply chain integration, which requires organizational and informational cooperation between business partners, aims at optimizing logistics processes by, among other things, eliminating paper circulation of documents, and thus minimizing errors associated with it. The role of the logistics provider is not only to rationally organize the implementation of logistics processes, but also to integrate the information of the business partners it serves. Logistics providers are generally classified into five groups depending on their role in a supply chain [Werner-Lewandowska and Kosacka-Olejnik, 2020]. For the purpose of this research, the characteristics of 2 of them were made: 3PL and 4PL, as shown in Table 1. Table 1 also indicates the range of services provided by

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logistics operators according to the NACE classification. NACE is the 'statistical classification of economic activities in the European Community' and is the subject of legislation in the European Union, which imposes the use of the classification uniformly within all Member States. It is a basic element of the international integrated system of economic classifications, which is based on classifications of the UN Statistical Commission (UNSTAT), Eurostat, as well as national classifications; all of them are strongly related each to the others, allowing the comparability of economic statistics produced worldwide by different institutions.

Table 1.Characteristics of a 3PL and 4PL

Role	Characteristics	Basic services sections according to NACE Rev. 2 classification
3PL	- integrated storage and distribution - integration and support of IT infrastructure - data tracking - own assets	Section H — Transportation And Storage Section J — Information And Communication Section K — Financial And Insurance Activities
4PL	- supply chain design - planning and optimizing supply chain logistics processes - re-engineering of supply chain processes - integration of services, systems, information - continuous innovation - technology as the basic resource - lack of own assets (technical logistics resources)	Section H — Transportation And Storage Section J — Information And Communication Section K — Financial And Insurance Activities Section L — Real Estate Activities Section M — Professional Scientific And Technical Activities Section N — Administrative And Support Service Activities Section O — Public Administration And Defence; Compulsory Social Security

Source: Own study based on [Chrąchol-Barczy et. al., 2017; Werner-Lewandowska and Kosacka-Olejnik, 2020, NACE Rev. 2, 2008].

Effective supply chain management requires information integration, which means that each piece of information should be entered into the enterprise information system only once [Kolinski and Werner-Lewandowska, 2021]. Such a solution ensures that data acquisition costs are minimized, that the collected and exchanged data are more consistent, and that the risk of errors is reduced. Furthermore, there should be no delays in data transfer within the supply chain, so the information entered in the system should be made available in real time to all users for whom it is relevant [Speier, Mollenkopf and Stank, 2008; Sassi, Arrivabene, and Romero, 2011; Kawa and Zdrenka, 2016].

Integration of information is achieved through communication channels and technologies that support the flow of information between business partners in the supply chain [Leuschner, Rogers, and Charvet, 2013]. Integration of chain participants is based on the application of modern information technology and broad partnerships [Hadas et al., 2015; Trojanowska, Varela and Machado, 2017]. Information technology capabilities and information sharing have a significant impact on logistics integration [Prajogo and Olhager, 2012; Horzela et al., 2018]. Information integration reduces the time required to generate data and information necessary for operational-level decision-making in logistics processes [Kolinski and Werner-Lewandowska, 2021; Golinska and Hajdul, 2011]. Acquisition of real-time data increases the readiness of companies for possible changes in the implementation plan of logistics processes.

The global supply chain relies on reliable communication, identification of transported cargo, and coordination of logistics processes. This is due to the need to maintain and coordinate the supply chain [Kawa, 2012]. Moreover, through electronic data interchange, paper documents and their associated costs are reduced in favor of EDI (Electronic Data Interchange) messages and information flow times between business partners are minimized. Furthermore, EDI should be considered as a solution to integrate information systems in the supply chain [Debicki and Kolinski, 2018]. Electronic data interchange is a response to the requirements of modern supply chains, which due to their complexity require a fast and reliable system of information exchange. EDI is treated as a technological solution as well as a solution with economic impacts [McLaren, Head and Yuan 2002; Nurmilaakso and Kotinurmi 2004; Moberg et al. 2002]. Research on the implementation of EDI has been conducted for many years [Collins, 1993; Riggins and Mukhopadhyay, 1999; Lee and Lim, 2005] and shows a diverse range of sectors and industries where EDI can be implemented [Klein, 1995; Laage-Hellman and Gadde, 1996; Angeles et al. 2001; Kim and Lee 2008; Bernardes &Miyake 2016; Bahija, Malika, and Mostapha 2016; Okano et al., 2017]. Evidence can also be found of the effectiveness of EDI implementation in business practice [Lee and Han, 2000; Lee, Lee and Kang, 2005; Zhou et al., 2018].

Companies began experimenting with EDI in 1970 and the first standards were developed and issued for the transport industry in 1975.

EDI provides a standard format that allows different business systems to communicate with each other. Business partners send and receive documents containing transactions such as invoices, purchase orders, waybills, etc. directly to their internal system or through an EDI network service provider. The process of sending a document requires three steps, Fig.1.

When identifying the data to be included in an EDI document, a company can use software programs to extract data from various systems when creating the document or having an employee manually enter the data. Using an extraction program makes the process more efficient but requires time to map the data sources of the existing system to the EDI application. Once created, the EDI document is transmitted directly to the trading partner's internal system or EDI network service provider.

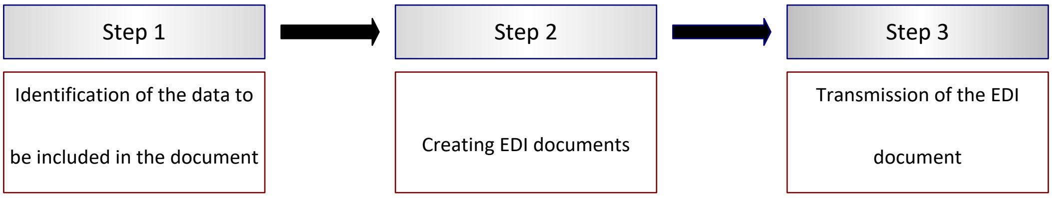

Fig. 1. The process of sending an EDI document, Source: own study.

The receiving of EDI documents mirrors the sending process. First, the trading partner receives the EDI document directly into its internal system or through an EDI network service provider. The EDI data is converted to be compatible with the internal system and then entered into that system. The information system sends the receipt confirmation to the sending partner.

Recently, EDI integration has moved to a cloud environment, called an integration platform. The cloud version of EDI allows companies to integrate through any type of protocol, format, and system, whether the company has IT systems that are maintained internally, managed by a third party, or are cloud-based. Cloud-based EDI solutions provide seamless updates without disruption to business operations.

Some general benefits of using EDI include the following:

- reduction of costs for personnel, consumables, and office/storage space,
- improved data quality by reducing data entry errors,
- reduced business cycle time from order to payment,
- improved business efficiency, by allowing staff to focus on critical issues rather than correcting errors,
- increased data security, through the use of passwords and program encryption,
- reduced disruption during the audit process,
- improved decision making as a result of having access to real-time information,
- increased corporate social responsibility and sustainability, due to reduced paper consumption.

EDI also has some disadvantages. Because trading partners must establish a connection between their information system and the EDI application, with new trading partners in the initial phase, these processes may take longer. Additionally, companies may have to redirect some IT resources in the initial implementation phase to data mapping and then to maintaining the EDI application. The process of implementing EDI into business reality can be:

- time-consuming and difficult,
- some trading partners may require additional information that needs to be modified,
- costly cause poorer visibility of information, using third-party EDI software, so companies may have difficulty tracking any errors that occur during data transmission.

In addition to technical problems, there are also problems resulting from the low number of EDI implementations at individual links in supply chains. The research aims to show the barriers related to EDI implementations in the opinion of 3PL and 4PL logistics providers.

RESEARCH METHODOLOGY

Scope of the study and conceptual model

The purpose of this research is to investigate the relationships between the size of a company and the role of logistics service providers in the electronic data exchange between 3PLs and 4PLs and their business partners. The conceptual model of the study is shown in Fig. 2.

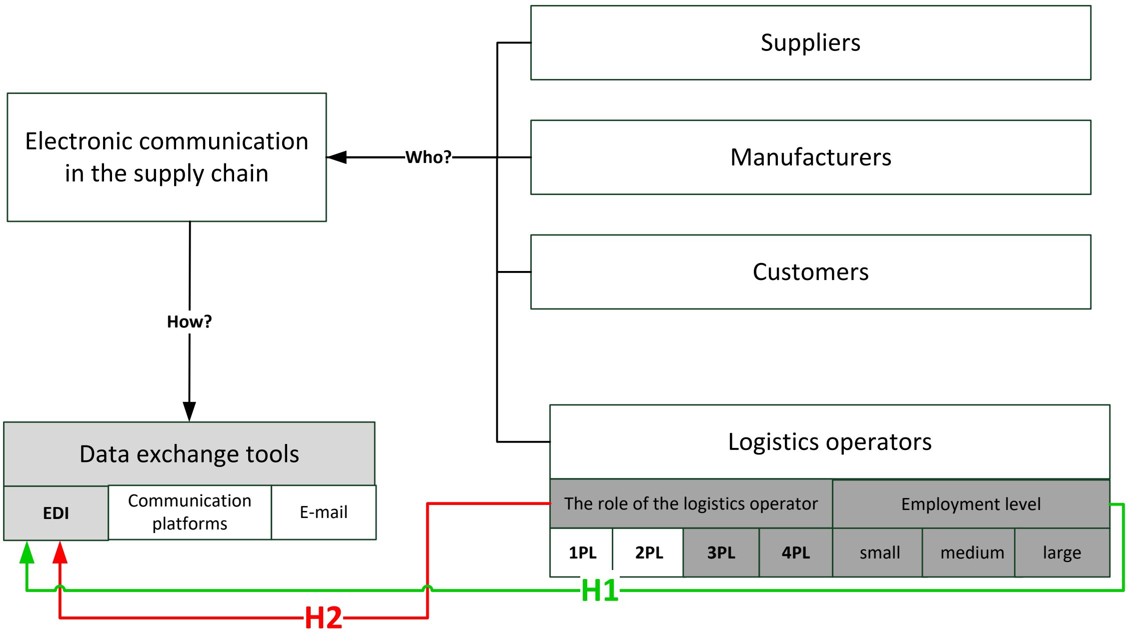

Fig. 2. Conceptual model
Source: own study

The research hypotheses have been stated as follows:

H1: Employment level determines the extent of problems in electronic communication between logistics service provider and customer.

H2: The role of logistics service provider determines the extent of problems in electronic communication between logistics provider and customer.

The hypotheses are justified by our previous work [Werner-Lewandowska and Golinska-Dawson 2021], in which it was identified that the size of the company (measured by the level of employment) influences the application of modern solutions in a supply chain. Second, we based on the previous studies on the role of logistics service providers in a supply chain with regard of the offered scope of services offered [Tang et al. 2019; Cichosz, 2018].

Data to verify research hypotheses

Verification of the set research hypotheses was carried out for the population of N=51 Polish companies providing transport and storage services. Companies were selected according to the volume handled annually in Poland, based on the TOP list of logistics providers [GS1, 2018]. The selection of the research sample can be considered representative and it allows one to draw conclusions on an EU scale. Poland is an interesting market for studies in the logistics sector. According to Eurostat data, the Polish logistics sector has a very high share in tonnes-kilometers of freight transport in the European Union [16.4% of the total of the EU] [EuroStat, 2019]. Poland has an advantage in cabotage activities. In 2018, Polish haulers were the main third country carriers in inter-country freight transport in the EU [Werner-Lewandowska and Golinska-Dawson, 2021]. According to CSO data, in 2018 transport and warehousing service providers represented 12% of enterprises in Poland [Werner-Lewandowska and Golinska-Dawson, 2021]. In addition, logistics service providers generate the largest impact on GDP among Polish service companies [Werner-Lewandowska and Golinska-Dawson, 2021].

The characteristics of the sample of 51 logistics service providers are shown in Tables 2 and Table 3. We take into account the size of company which is measured according to the EU classification by number of employees and is called in this study “employment level” (Table 2).

In Table 3 the structure of the research sample is presented with regard of the logistics provider role.

Table 2. Basic information about the researched companies – employment level

Characteristics	Responses [%]
fewer than 10 employees	3,92%
from 10 to 49 employees	17,65%
from 50 to 250 employees	21,57%
more than 250 employees	56,86%

Source: Own study

Table 3. Basic information about the researched companies – role

Characteristics	Responses [%]
3PL	64,71%
4PL	35,29%

The research was conducted in 2018 among the leading logistics providers doing business in Poland. More than 77% of them are medium- or large-sized companies. More than 60% offer third-party logistics [3PL] services. According to the theory of estimation in operational research, the minimum research sample that guarantees the representativeness of the results is n=30. The confidence level should not be less than 85% and the maximum error greater than 18% [Balakrishnan and Basu, 1996]. The analysis carried out by the authors allows us to conclude that, assuming a maximum error of 15% and a confidence level of 95%, the research sample of 43 companies should be considered representative [Domanski and Kolinski, 2020].

The statistical sample of 51 logistics providers is representative and allows to draw the obtained conclusions.

The respondents were asked to: *What are the most common problems in electronic communication between your company and customers?*

- The respondents were able to indicate the following responses (multiple choice):
- Insufficient knowledge about EDI,
- Inadequate IT systems of customers,
- Customers do not want to implement EDI,
- Lack of a single standard solution,
- Long time and high costs of EDI implementation.

The percentage structure of the respondents' responses is shown in Fig.3.

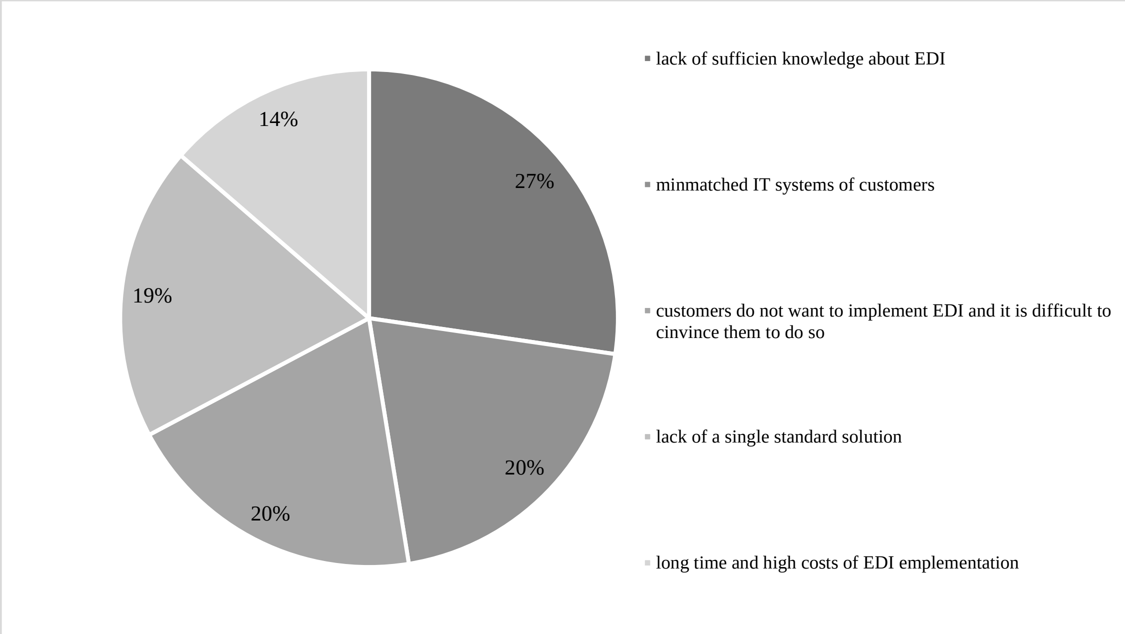

Fig.3. Structure of respondents' answers.
Source: own study

Analyzing the responses of the respondents (Figure 3), it can be concluded that the lack of sufficient knowledge about EDI is the most common problem in communication between logistics providers and their customers. This problem is also the most common barrier to implementing EDI with business partners. An in-depth analysis of respondents' indications has shown that this problem concerns all micro companies that are 4PLs, whereas in the case of larger companies, this problem was more often indicated by 3PLs (as shown in Fig. 4).

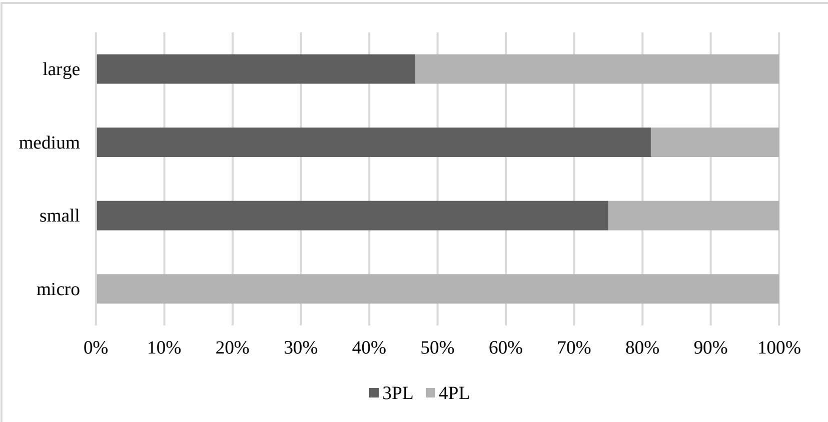

Fig. 4. Respondents' indications of insufficient knowledge about EDI as a communication problem.
Source: own study

Initial conclusions from the respondents' responses were further statistically analyzed to verify the research hypotheses. Data were analyzed using the statistical package R 4.0.2. For each dependent variable, a Bayesian regression with company size and logistics provider role was run as predictors to determine whether reliable differences between groups were present in the survey data. The size was coded 0.5 for large firms and -0.5 for other firms, while the role of 3PL was coded 0.5 and 4PL was coded -0.5. The regression weights of each predictor represent the estimated difference between the groups. Binary dependent variables (yes-no questions) were analyzed using regression.

In Bayesian statistics, inference is based on a posteriori distributions of the parameter (e.g., regression weights). Results are usually summarized by the mean and the 95% credible interval (95% CI). If the 95% CI excludes zero, the parameter value can be considered statistically reliable. The models were built using the brms package [Bürkner, 2017]. The prior logit scale regression weights were assumed to be normal (0, 1), ensuring uniform coverage of the probabilities. Four parallel chains with 2000 iterations (including 1000 for warm-up) were used for a posteriori approximation, and every second iteration was logged to reduce autocorrelation in the chains. The sampling procedure was efficient, as judged by analysis of the results, autocorrelation graphs, and the parameter $R < 1.01$.

VERIFICATION OF HYPOTHESES

Table 4 shows the results of Bayesian logistic regressions conducted with responses from respondents as the dependent variables, and Figure 2 shows the proportion of "YES" responses to the questions asked, depending on the size and role of the provider, where Me, SE and LI and UI are the median, standard deviation, and lower and upper bounds of the 95% credible interval of the a posteriori distribution of the regression weights.

Table 4. Hypotheses testing

Hypotheses	Predictor	Me	SE	LI	UI
		lack of sufficient knowledge about EDI			
H1	Company size - Employment level	-0.73	0.54	-1.76	0.32
H2	The role of the logistics provider	-0.21	0.54	-1.25	0.77
		mismatched customer IT systems			
H1	Company size - Employment level	-0.83	0.53	-1.82	0.24
H2	The role of the logistics provider	0.47	0.52	-0.54	1.47
		customers do not want to implement EDI and it is hard to convince them to do so			
H1	Company size - Employment level	-0.78	0.53	-1.82	0.27
H2	The role of the logistics provider	-0.06	0.55	-1.12	1.05
		no one standard solution			
H1	Company size - Employment level	0.06	0.51	-0.94	1.02
H2	The role of the logistics provider	0.32	0.53	-0.7	1.39
		long time and high costs of EDI implementation			
H1	Company size - Employment level	0.47	0.56	-0.62	1.62
H2	The role of the logistics provider	0.41	0.57	-0.7	1.59

Source: own study

The distributions of the affirmative answers indicating the determinants of problems in electronic communication between logistics operators and customers (black dots and red figures) as a function of company size and operator role are presented in Figure 5.

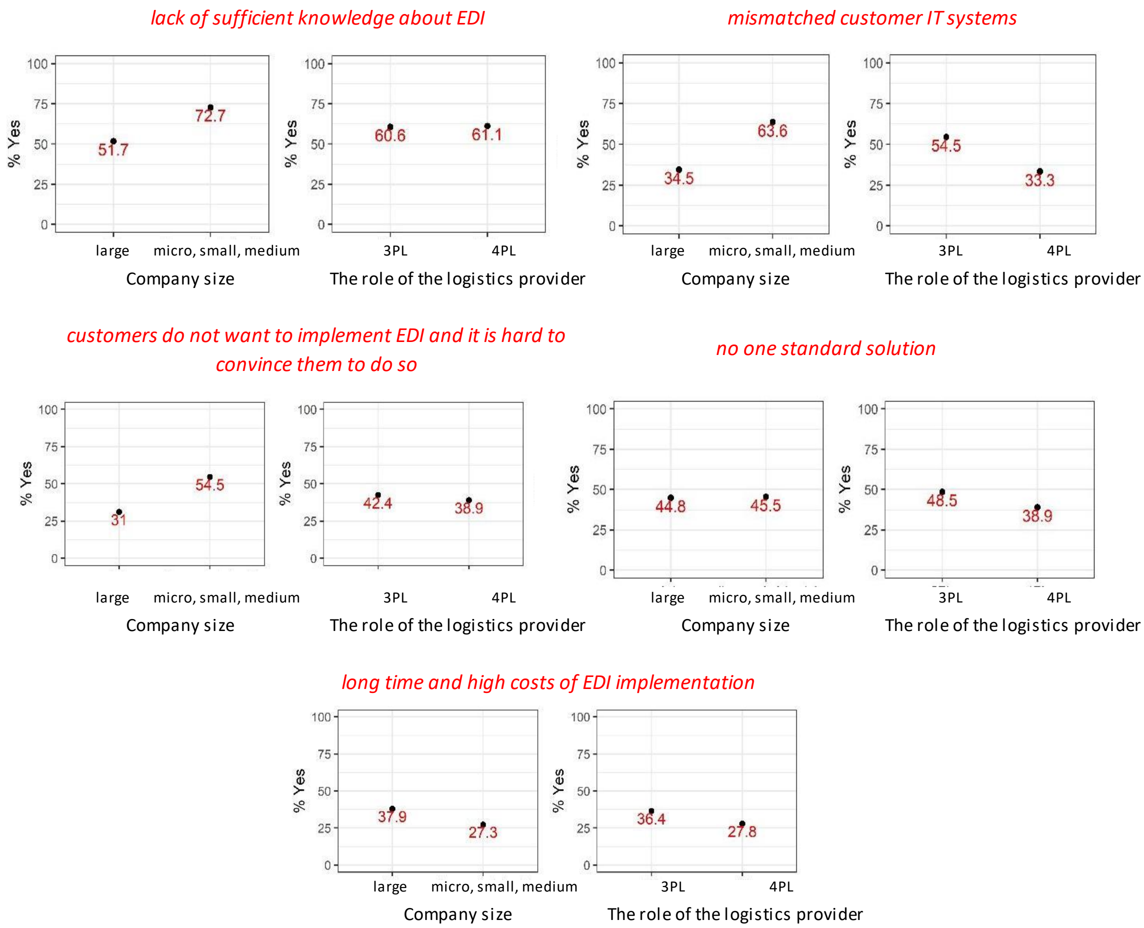

Fig.5 Percentage of respondents' affirmative answers
Source: Own study

DISCUSSION

According to the data presented in Table 4, in all analyzed cases the reliability intervals contain zero (LI and UI have opposite signs), which means that no statistically reliable relationship was observed between the predictors, employment level and role of the logistics provider and the dependent variable, the most common problem in electronic communication between the logistics provider and customers. On this basis, it should be concluded that the verified research hypotheses are not supported by the research data. Therefore, they may be rejected in favor of hypotheses 0 such as:

H1: The problems in the IT communication between the logistics service provider and the customer do not depend on the size of the company (measured by the variable level of employment);

H2: The role of the logistics provider does not influence the extent of problems in the electronic communication between the logistics service provider and its customers.

Based on this, the conclusion is that the size of the logistics provider (measured by the number of employees, called the “employment level here) and its role in the supply chain do not affect the extent of electronic communication problems within the supply chain.

Analyzing the values of individual statistics such as median, standard deviation, and lower and upper bounds of 95% credible interval of a posteriori distribution of regression weights, it can be concluded that, in the opinion of logistics service providers, regardless of their size and role in the supply chain:

lack of sufficient knowledge about EDI, mismatched customers' IT systems, and customers' reluctance to implement EDI are not problems in electronic communication between a company and customers,

lack of a single standard solution and the long time and high cost of EDI implementation are problems in electronic communication between a company and its customers.

CONCLUSION

The research allowed us to obtain primary data on the problems in electronic communication between logistics service providers and customers. Statistical analysis allows identification of the main barriers associated with EDI implementations at logistics partners. These barriers include the lack of a single standard solution and the long time and high cost of implementation.

The obtained research results have practical implications for 3PLs and 4PLs. They indicate barriers to the implementation of EDI at their business partners, which translates into cooperation in the supply chain. The results of the research can also help providers of EDI solutions, as they indicate what causes the lack of widespread implementation of this solution in companies. Therefore, they should strive to reduce implementation time and costs.

Further research will focus on empirically identifying the enablers for cooperation in a supply chain with EDI solutions.

Knowledge of barriers to the use of electronic data exchange in the supply chain is essential in order to assess and analyze the current level of digitalization. The so-called Digitalization Index [Szopa and Cyplik, 2020] is used to measure the overall effectiveness of the work in digitizing processes and transforming business models through the use of innovative digital technologies. This index consists of 21 subindices, among which is an indicator expressed as Annual sales volume realized through computer networks (websites, EDI and other methods of electronic data exchange, excluding email) [Szopa, and Cypli, 2020].

Modern technological solutions (such as the use of cloud technologies, EDI, or flow tracking standards) increase the positive effects of logistics coordination [Kmiecik, 2023]. This is because the use of EDI enables the centralization of demand and logistics coordination by the 3PL operator in the distribution network and can provide the manufacturer with better information about sales, plans, deliveries, and inventories. The 3PL will be able to support the manufacturer's demand plans. It will also be able to modify create contingencies using knowledge of flows in the distribution network [Kmiecik, 2023].

The barriers to electronic data exchange between business partners in the supply chain are worth noting in the context of the benefits of EDI. Existing EDI technologies combined with Blockchain and Big Data analytics solutions can offer a flexible and updated solution to transfer data across different platforms [Blakely et al., 2021]. Analytical techniques can process and build models for both structured and unstructured data. The execution of these techniques is often automated and can run continuously, accepting large portions of data for analysis. EDI transactional data can be transformed based on the application in question and the area of transactional data that the EDI service wishes to explore. On the basis of the parameters available in the data, a combination of models can be built for analysis. In addition, convolutional machine learning techniques and deep learning algorithms can be used to build AI models to perform complex tasks to obtain the required output of big data applications from EDI transactional data [Blakely et al., 2021].

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ORIGINAL PAPER

A SYSTEMATIC REVIEW OF THE USE OF ORGANISATIONAL AND MANAGEMENT THEORIES IN REVERSE LOGISTICS STUDIES

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ABSTRACT. Background: Reverse logistics studies have received increasing attention in academic, organisational, and management research. Researchers have contributed to this field by borrowing theories from sustainable business research. However, there is a lack of literature reviewing the development and contribution of reverse logistics studies in organisational and management theories. By identifying the most frequently used management theories, this paper fills the gap and describes the theoretical contribution of reverse logistics papers to organisational and management theories.
Methods: Using the vote-counting technique, this article reviews 122 papers published between 2005 and 2021 to assess how organisational and management theories developed in the studies of reverse logistics.
Results: The analysis indicates that, while some, such as triple bottom line and critical success factors, have been frequently employed, the relation between reverse logistics and sustainability and other organisational theories remain undeveloped. It also discovered that the research topics only focused on product and material recycling, but few on product return and exchange logistics.
Conclusions: First, there is a huge gap in organisational and management theories and reverse logistics studies**.** It is suggested that scholars involved in reverse logistics studies can explore more connections between reverse logistics strategies and management theories in future research. Second, more theories should be used in addition to triple bottom line and critical success factors in reverse logistics research**.** Furthermore, although some incorporated other factors into the management theories and developed a framework after examining their interrelationship, little contribution has been made to the theories themselves. Additionally, more discussion of reverse logistics in the field can focus on product return and exchange logistics.

Keywords: reverse logistics, organisational and management theories, systematic literature review, sustainability, theories development

INTRODUCTION

The surge of electronic and electrical products and environmental concerns fuels the studies on Reverse Logistics (RL). In recent years, academia and business have highlighted the importance of RL for SCM because of environmental and social responsibilities and the economic benefits of used products. Therefore, RL is often connected to sustainability, remanufacturing, or strategy.

Although previous reviews discussed environmental issues and circular economy [Islam et al., 2021] or Green Supply Chain Management (GSCM) and management theories [Liu et al., 2018], there is still a lack of research on the use of organisational and management theories in RL studies. Therefore, this article aims to address the gap by identifying the main management theories adopted in RL and sustainability studies and analysing the contribution of these studies to theories by meeting the following objectives: (1) provide a review and synthesise the literature focused on RL; (2) summarise previous research over the past years and identify the limitations of these studies in terms of theories and methodologies; and (3) propose solutions to the research limitations and suggestions for future research. These goals are crucial for improving RL research.

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This paper is organised as follows. The next section presents the scope and research methods. Section three demonstrates the results, including all management theories employed and highlighting the nine frequently used. Section 4 summarises the descriptive evaluations of the reviewed studies. The final section discusses the results and future research directions.

SCOPE AND RESEARCH METHOD OF THE LITERATURE REVIEW

This paper systematically reviews management and organisational articles concerning RL and sustainability published between 2005 and 2021. All papers were selected in the Web of Science. Three criteria applied for the selection are as follows: (1) the articles must relate to the keywords, RL, and sustainability, based on organisational and management theories. Keywords plus were not considered; (2) the research considers academic journal articles, including peer reviewed articles and early online publications to ensure objectivity; (3) the review only includes articles in English (see Figure 1).

The study first focuses on the articles discussing 'RL' and 'sustainability' associated with the term 'theory' in titles, abstracts and author keywords. This phase led to 41 papers referring to 21 theories, reflecting that some theories were used in more than one article. Subsequent searches concentrate on the specific theories identified in the initial research by combining 'RL' and 'sustainable' with the specific name of a theory (eg TBL and CSF) in the search algorithm. This round of search returned 81 papers and 29 additional theories. These theories were then included in further theory-specific searches. Finally, there were 132 papers adopting 50 theories.

The next step is to select the theories of related papers that could be classified as organisational and management theories. Since the classification of management theories remains undefined. The author adopted the classifications provided by Daddi et al. [2018], which identified 72 organisational and management theories. Theories identified by the former bibliographic research, but not included in the classifications mentioned above, were excluded from the analysis, as they were not pertinent to management theories. As a result, 29 of 50 theories were eligible for analysis (see Table 1). Therefore, the number of articles dropped from 132 to 122 articles associated with the 29 selected organisational and management theories. This paper only considers the nine organisational and management theories that are most frequently used in reverse logistics studies (see Table 2). However, according to the reference numbers, the manuscript selected only the most representative articles (61 papers in total) under the nine theories most applied nine theories (see Table 3).

RESULTS

The selected theories highlight a prevailing understanding of RL as a strategy in management and organisational studies at the microlevel rather than a societal, ethical, or macrolevel.

The descriptive summary of 61 contributions is listed in Table 4. This review analyses the literature in three dimensions: (1) annual contributions; (2) theoretical distribution; (3) and research characteristics: country/region, research methods, classification of studies, variables applied to RL, research field and industrial sector, and case study and sampling situation.

Annual Contributions

The studies on RL and sustainability increased slightly from 2005 to 2013, but were still quite inadequate, with only nine papers in total (see Figure 2). In this period, research was mainly on the RL system, Reverse Supply Chain (RSC), sustainability, Closed-Loop Supply Chain (CLSC), Green Supply Chain (GSC) and innovation issues. Few explored RL management issues [e.g., Presley et al., 2007; Hsu et al 2013]. With the surge of e-businesses and environmental awareness in logistics, the studies witnessed a noticeable increase from 2013 to 2018, reaching 38 papers, 18 papers of which published in 2018. The diversity and depth of discussion showed in the selection of the themes, ranging from remanufacturing, recycling, and CLSC to the RL implementation and operation process. Most of the research discussed the issue in emerging market such as India, Malaysia, and China throughout the period. This was attributed to the rapid development of e-commerce.

Theoretical Distribution

The initial paper that applied management theories to RL was in 2005, employing Institutional Theory (IIT) to develop a RL monitoring system to control the reverse flow of materials through marketing channels [Richey et al., 2005]. However, TBL is the most applied theory, with 18 papers, followed by Resource-based Theory (RBT) and Critical Success Factors Theory (CSF), with 11 and 8 articles, respectively. The top three theories were used annually between 2014 and 2021 and accounted for 64.1% of all RL research. In particular, studies that used RBT contributed eight articles over the last three years, accounting for 13.1% of the gross amount. This demonstrated that RBT might become the new cutting-edge organisational and management theory in RL research.

Research Characteristics

Targeting Country/Region Analysis

The analysis finds that RL studies receive more interest in developing countries and were centralised in specific countries or regions. Among the 61 reviewed articles, 23 focused on Indian RL issues, followed by Europe (7), China (3), Chinese Taiwan (5), Malaysia (3), Bangladesh (2) and South Africa (2). RL enjoys a high prevalence in India, and scholars wrote articles evenly and annually from 2015-2021, and the trend in Europe was from 2015-2018. In comparison, RL research publications in Taiwan started from 2014 to 2016 and Malaysia from 2013 to 2019. The contributions of Brazil, China, South Africa, and Bangladesh RL contributions began between 2019 and 2020. Therefore, it could be summarised that RL issues have drawn more academic attention in most BRICS countries.

Research Methods

The review found that case study, theory analysis, questionnaire, literature review, and interview were the primary research methods. Most of the papers (26) employed case studies, accounted for 42.6%, and specifically, nine applied TBL, five in CSF; DCT, IIT and FST contributed three papers, respectively. The following was the theory analysis of 16 papers in total, TBL contributed seven papers, both GE and CSF counted three papers. Then was the questionnaire (ten articles), six of which were conducted by RBT; the interview contributed seven articles. Most case studies examined theories with practice but were limited to automobiles and electrical and electronic equipment. This indicates that the study of RL issues still needs more practical experience and industrial cases in other sectors to apply the organisational and management theories. Moreover, with the development of global business and manufacturing industries, such as automobiles, electrical and electronic products, pharmaceuticals, and e-business, and the need for sustainable development, the practice and research of RL have become more critical than ever. The cooperation between academia and industries has become a proper and efficient approach to simultaneously promoting the research and sustainable development of these industries.

Most of the papers combine modelling analysis with case studies (26) or theoretical analysis (16). It has also been found that there were hardly commonly applied research methods in each theory. The explanation for this can be that the RL study is still in the initial stage and scholars need to explore various solutions using different approaches. Specifically, under TBL, CFS and DCT, there are in total eight articles used in Decision-Making Trial and Evaluation Laboratory (DEMATEL) [e.g., Mathivathanan et al., 2018]. Nine were built on GT and IIT [e.g., Dubey et al., 2017]. Another six contributions adopted Fuzzy related methods, four of which were based on FST [e.g., Cui et al., 2021]. In addition, four papers focused on Partial Least Square (PLS), focusing on TBL, RBT, DCT, and ST [e.g., Kumar and Rahman, 2016]. Four research applied Multiple-Criteria Decision-Making (MCDM), among which two were based on CSF [e.g., Kannan, 2018; Gardas et al., 2018].

Classification of the Studies

The selected theories included common theoretical approaches to the corporative relationship between individuals, organisations and stakeholders, and industry/system-level studies (see Table 5), such as TBL [Kumar and Rahman, 2016]; CSF [Luthra et al., 2018], Stakeholder Theory (ST) [Brockhaus et al., 2016], GT [Yan et al., 2018], and the Planned Behaviour Theory (PBT) [Brockhaus et al., 2016]. Other influential approaches to decision-making and behaviour studies, corporate governance, and strategic management were included, such as the RBT [Bag and Gupta, 2020]. Second, mathematical approaches to industry/systems include Fuzzy Set Theory (FST) [Cui et al., 2021] and IIT [Li et al., 2019]. Such research provides decision-making and behavioural, environmental, strategic management, and corporate governance suggestions on crucial organisational, industrial, and business issues, such as prioritising the 3PRLPs [Pourjavad and Mayorga, 2018], CLSC network [Darbari et al., 2019], the unexpected situations under embedded environmental consciousness [Nishant et al., 2016], the implementation of GSCM strategies [Liu et al., 2020], and RL monitoring system for controlling reverse flows of materials through marketing channels [Richey et al., 2005]. Finally, psychological theory and its extension in RL drivers and marketing theory (IIT) in strategic resources [Hsu et al., 2013].

Table 5 concludes the theories selected according to the field of study and the unit of analysis adopted in these articles. The number within brackets indicates the articles within the specific field of study, focusing on the specific unit of analysis. The table shows that scholars adopt some theories with a specific unit of analysis and in a specific field of study. In contrast, TBL, RBT, CSF, DCT, IIT, ST, and PBT demonstrate the capacity to be adapted to different fields and units.

Variables Applied to RL

Most of the articles that used TBL applied economic, environmental and social factors as the research variables. Among these, Govindan et al., [2015] and Lu et al., [2016] only adopted environmental factors, Bradley et al., [2018] and Waqas et al., [2021] used economic and environmental factors, while Schenkel et al., [2015] applied environmental and social factors. These indicate that environmental issues are the focus of RL research with TBL.

There are 11 papers employed RBT all the papers are empirical studies, using strategies as the shared variables. Huang and Yang [2014], Morgan et al., [2018], Paras et al., [2019], Shaharudin et al., [2019], Bag and Gupta [2020], and Nag et al., [2021] also added resources as other factors.

Research Field and Industrial Sector

Most of the reviewed research consisted of multiple fields or topics, and some papers focused on more than one aspect [e.g., Ashby, 2018; Waqas et al., 2021]. Among these, 23 articles studied manufacturing topics [e.g., Huang and Yang,2014; Agrawal et al., 2016a; Yan et al., 2018]. 20 articles discussed management issues [e.g., Shaharudin et al., 2015; Mangla et al., 2018; Liu et al., 2020], both sustainable related issues and topics of the automobile industry contributed 19 papers [e.g., Kumar and Rahman, 2016; Biswas et al., 2018]. 16 articles focused on GSC [e.g., Hsu et al., 2013; Jayaram Avittathur, 2015], and 13 papers conducted CLSC research [e.g., Schenkel et al., 2015; Darbari et al., 2019]. Meanwhile, electronic-related topics contributed 11 papers, while both environmental and circular supply chain topics recorded six papers [e.g., Bag et al., 2020; Cui et al., 2021].

Case Study and Sampling Situation

According to Table 4, 26 articles were case studies, 12 of which explained the firm size. Nine cases were conducted at large companies, two discussed small, medium, and large companies, while only one considered medium companies.

Among the 26 case studies, all the papers collected primary data. For studies that used primary data by questionnaire, the sample size (excluding the interview) ranged from 12 to 2000 with an average of 644, the average response number was 203, and the average response rate was 38.9%.

REVERSE LOGISTICS STUDIES WITH ORGANISATIONAL AND MANAGEMENT APPROACHES: THE TOP THREE USED THEORIES

1. THE TRIPLE BOTTOM LINE THEORY (TBL)

The TBL consists of three parts: social, environmental, or ecological, and financial and evaluates performance from a broader perspective to create more business value [Slaper and Hall, 2011]. It has been applied in several studies to explore the approach to sustainable development and the measurement of social and ecological categories in addition to the financial performance of enterprises.

TBL has been frequently applied to the studies of RL in the electronic industry. Agrawal et al. [2016a; 2016b], Kumar and Rahman [2016] and Flygansvaer et al., [2018] researched the RL of the electronic industry based on TBL. The studies found that outsourcing decisions shape the performance of the reverse supply chain (RSC), and product returns are positively related to RL operational performance and critical to an organisation's sustainability. Managers who seek to enhance TBL performance should foster an ecologically orientated culture.

Other scholars utilise TBL to study the RL operation model. Bradley et al. [2018] demonstrated the demand for a total life cycle cost model that serves as the primary engineering economic model based on TBL and found that sustainability is a three-legged stool with the economic leg as the centre. Meanwhile, Darbari et al. [2019] and Mota et al., [2018] proposed that sustainable RSC can be achieved by TBL. Developing a Sustainable Reverse Logistics (SRL) model to adopt RL practices in existing supply chains has emerged as an essential incentive for manufacturers to gain financial and competitive advantage. Devika et al. [2014] researched the multi-objective, multi-echelon RL network design. The findings indicated that network centres that require lower opening costs create more opening and operating job opportunities.

Generally, TBL is the most applied theory in RL research. It is frequently discussed and associated with the electronic industry, developing the operation model, partner selection, and CLSC network configuration. It has also been found that, among the three variables, researchers are more concerned about environmental issues.

2. RESOURCE-BASED THEORY (RBT)

RBT, also called Natural RBT (NRBT), is a managerial approach that determines the strategic resources that a firm can exploit to achieve a sustainable competitive advantage. Such an advantage is based on the idiosyncratic and heterogeneous bundles of resources, assets tangible and intangible, and processes that a firm can control [Barney et al., 2001].

RBT has been used to study RL in the clothing industry. Ashby [2018] investigated a CLSC through an in-depth case study of a UK-based clothing firm and showed that strategic resources, shared vision, and principles are essential between the focal firm and its Reverse Value Chain (RVC). Paras et al., [2019] further evaluated the RVC in the industry and indicated that low operating cost, skilled human resources, business knowledge and location are internal success factors.

Some scholars applied RBT to study the impact of human resources or drivers on RL. Bag and Gupta [2020] found that green human capital positively influences RL adoption and remanufacturing operations, while top management commitment and sustainability culture moderate on path availability, green human capital, and RL. Nag et al. [2021] utilised RBT to identify and evaluate drivers and sub-drivers. They proposed that the firm focus on circular value marketing, circular services, circular product design, and reverse flow.

RBT also focuses on the study of SRL. Morgan [2018] examined a structure-conduct-perform linking resource commitment to future sustainable SCM, RL and operation, and they believe that resource commitments could be employed to develop a SRL capability and reduce the relating environmental impact. Nishant et al. [2016] integrated NRBT and materiality and revealed that Indian firms were concerned with RL, product recycling and improving supplier environmental performance.

In general, RBT has been used to RL in issues including the manufacturing industry, clothing, SRL, and the impact of human resources or drivers on RL, which is a major application of RBT to the study of RL. For all the variables of RBT, the researchers mainly focused on the strategies.

3. CRITICAL SUCCESS FACTORS (CSF)

CSF or critical success activity is required to ensure the success of a company or an organisation's success. The theory was initially employed in the areas of data analysis and business analysis and analysed the central success factors in a company [Rockart, 1979].

CSF has been frequently applied to the RL industry and activities and has been considered as a systematic approach to improve environmental impacts and ensure sustainability in business. Sachin et al., [2015] discovered that industries were enthusiastic about adopting RL activities, although facing several difficulties, such as insufficient knowledge and resources regarding RL implementation. Therefore, they suggested that companies concentrate on the effectiveness and efficiency of RL adaptation.

Other scholars adopt the theory to analyse RL in terms of sustainability or the environment. Based on the Indian automobile industry, Luthra et al. [2017] provided a scientific model that offers comprehensive information on supplier selection for sustainability via using an integrated AHP-VIKOR approach. The study concluded that the environmental dimension achieves the maximum priority weight and that environmental costs received the highest rank. Gardas et al. [2018] and Kannan [2018] also discussed the same issues in the automobile industry. Silva and Fontana [2020] proposed a CSF survey procedure in reverse flow inventory management. Their findings provided a methodology to survey some CSF situations, which made the cyclic analysis and a comprehension of multiple perspectives critical in group decision-making environments.

The CSF is used mainly in the management or decisions of the RL, primarily focusing on the automobile industry. The findings revealed that technology involvement and green practice factors are the most important among CSFs, implying that sustainable management requires the most responsiveness. The researchers put management as the most critical variable.

REVERSE LOGISTICS STUDIES WITH ORGANISATIONAL AND MANAGEMENT APPROACHES: THE LESS FREQUENTLY USED THEORIES

4. INSTITUTIONAL THEORY (IIT)

IIT answers the central question of why all organisations in a field tend to look and act the same. IIT and its evolution as the new institutionalism theory have been widely debated in environmental management studies.

The theory has been frequently investigated for the drivers or motivations for firms or individuals to participate in the RL or GSC. Hsu et al. [2013] also developed four constructs under ITT that motivate firms to adopt and implement GSC. Similarly, Li et al. [2019] examined how the interaction of external and internal pressures influenced the top management championship of green practices in China. The results concluded that the top management championship significantly impacted the adoption of green practices.

Other scholars emphasise developing a framework or system to address the current issues on product return and exchange logistics. Shaharudin et al. [2015] uncovered that Malaysia's five electrical companies had adopted a single return management programme to handle different product returns based on IIT to achieve sustainability. Richey et al. [2005] developed an RL monitoring system to control the reverse flows through marketing channels in emerging economies. Their research also developed and scaled a partner control model for managers and academics.

IIT is used most to explore the drivers or motivations for firms or individuals to participate in the RL or GSC. The theory also discussed or developed the RL system or other current issues relating to RL. The most concerning variable of IIT applied to RL is organisational behaviour.

5. STAKEHOLDER THEORY (ST)

ST is one of the most popular management theories and has also been widely debated. The theory concentrates on dealing with the role of stakeholders in company strategies. Based on the theory, stakeholders' involvement in corporate decisions is not only an ethical approach but also a strategic variable to gain competitive advantages [Plaza-Ubeda et al., 2010]. Scholars have frequently applied ST to several works in different fields, and it has been frequently applied combining with other theories.

Schenkel et al. [2015] researched integral value creation in CLSCs by distinguishing between multiple types of business value, strategic success factors, and multiple groups of stakeholders that influence and are influenced by CLSC activities with ST. They found that CLSC activities create opportunities and reduce risks for the focal company and its primary and secondary stakeholders.

Wijewickrama et al. [2021] studied the increasing detrimental effects on sustainability and the RL Supply Chain (RLSC) employing 21 semi-structured interviews representing five external stakeholder categories. They explained that regulatory uncertainties are the root causes that influence quality assurance in the RLSC.

ST is comprehensively applied to the creation of integral value in CLSC and increasing detrimental effects on sustainability and RLSC. It has also been found that the internal and external stakeholders are the key variables.

6. DYNAMIC CAPABILITIES THEORY (DCT)

There are many definitions of the theory, Teece et al., [1997] defined DCT as "the firm's ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments." To date, studies on DCT have multiplied over the past two decades, leading to an intensively studied and complex management theory.

There are three case studies related to RL to DCT. Munny et al. [2019], Bag et al., [2020], and Bhatia [2021] discussed the relationship between technological capabilities/innovation and environmental strategies and found that workplace health and safety practises are the most critical impactors for the social sustainability of a footwear manufacturing company's Supply Chain (SC).

The case study is the most frequently used method of DCT in RL research. The relationship between organisational behaviour and sustainability or social responsibility has been mostly discussed. Additionally, the strategy was the most crucial variable in all the selected papers.

7. FUZZY-SET THEORY (FST)

FST is a decision-making approach in managerial perspectives in firms that depends on several criteria, such as qualitative perceptions provided by humans, data shortage, and uncertainty in judgements. The computed results can be misleading if fuzziness during recording uncertain situations is inappropriately handled [Zadeh, 1996].

Some scholars apply FST to study the RL of the electronic industry. Darbari et al. [2019] designed a CLSC network for an Indian laptop manufacturer with fuzzy goals of TBL impact. The results showed the importance of employing the CLSC model as a decision approach.

FST is also conducted for the research of SCM. Stekelorum et al. [2021] examined how different combinations of internal and external GSCM influence the operational and financial performance. The results showed that a combination of green supply and eco-design packaging enhances the performance of small TPLs.

However, other researchers use FST to evaluate prioritising or environmental issues. Cui et al., [2021] investigated the reduction of resource waste and improved resource utilisation efficiency. The results showed that technological innovation encourages consumers to return used products and buy remanufactured products.

The fuzzy performance importance index is the most applied variable for all six papers, and this theory is used in implementing GSCM strategies and the finding the best solution. Furthermore, FST also discussed the evaluation of prioritising environmental issues.

8. GAME THEORY (GT)

GT examines the decisions of individual players to win a game against one or more competitors. Players are abstract, intelligent, individual agents who act in pursuit of their own limited goals in an abstract setting [Miles, 2012]. The theory has been involved in management, business, economies, political science, and international environmental agreements.

GT has been frequently applied to the modelling analysis of RL. Yan et al. [2018] used GT to investigate the expenses and gains of two potential sustainability options (I: owning the reverse channel and collecting cores directly; II: outsourcing operations to third-party remanufacturers). They found that compared to Model I, OEM conducting take-back operations can achieve better results for TBL situations.

The application of GT also focuses on remanufacturing technology. Shekarian et al. [2021] investigated the effects of carbon emission and remanufacturing simultaneously in a dual channel in both forward and RL and found that consumers are generally more sensitive to the price and gained profits rather than the carbon footprint when purchasing remanufactured products due to their doubts on the quality and technology level of these products.

GT has been frequently used in the modelling analysis of RL, such as integrating CLSC network design to find a better solution. Furthermore, remanufacturing technology is another focus of the GT's application to RL studies to provide possible development strategies. Therefore, the researchers considered strategy as the most crucial variable.

9. THEORY OF PLANNED BEHAVIOUR (TPB)

Identifying the cognitive drivers of RL has aroused general interest in management and consumer research. The original TPB framework consists of three elements: behavioural intention, subjective norms, and Perceived Behavioural Control (PBC). TPB is frequently adopted to investigate the cognitive processes of several RL behaviours [Tikir and Lehmann, 2011].

TPB has been applied to sustainable/RSC and logistics over the past seven years. Brockhaus et al. [2016] conducted an inductive empirical study of 28 European and US companies and then developed a framework for benchmarking product sustainability efforts. The article explored the dynamics of the supply chain related to RL's sustainable product programmes and empirically developed a framework to align efforts throughout the supply chain to bring sustainable products to market. Dixit and Badgaiyan [2016] discussed the acquisition from consumers by determining the psychological contributors to the intention on e-waste return. The findings indicate that the intention is a mediating variable in predicting return behaviour. Furthermore, perceived behavioural control, subjective norms, moral norms, and willingness to sacrifice were the antecedents to the return intention.

There are only two papers applying TPB to the study of RL. Researchers discussed benchmarking product sustainability and e-waste acquisition from consumers. Behavioural control is the variable covered in both papers.

DISCUSSION AND FUTURE DIRECTIONS

The review process confirms that RL studies lack a clear theoretical contribution to the development of organisational and management theories, since only a few organisational and management theories were mentioned in RL papers. In general, TBL (18 papers), RBT (11 papers), and CSF (8 papers) are the most commonly used management theories in the existing literature.

Quantitative studies are the most commonly adopted approach for the top five theories. Table 6 indicates that some scholars limit their topics to a specific area. 12 contributions developed a new hybrid approach to evaluate and select partners based on TBL with quantitative studies [e.g., Presley et al., 2007; Devika et al., 2014]. Furthermore, some articles employed two theories simultaneously, such as the use of FST and ST in the article by Darbari et al., [2019]. For the case of CSF, four quantitative articles and one qualitative article [Silva and Fontana, 2020] collected the primary data for analysis. On the contrary, Mangla et al., [2018], Gardas et al., [2018], and Thakur and Mangla [2019] adopted secondary data. The similarity in data collection was found in all seven contributions based on quantitative and qualitative contributions for GT. The articles adopting RBT include quantitative articles [e.g., Huang and Yang, 2014; Morgan et al., 2018], a qualitative article [Paras et al., 2019], and a conceptual article [Li et al., 2019], and these articles collected primary data. Nag et al. [2021] adopted the secondary data and applied ST. For FST, Stekelorum et al. [2021] adopted the primary data, and the other papers adopted the secondary data.

The less used theories highlight a different distribution from the top three theories used among the three categories of research methods. According to the year of publication, quite surprisingly, most papers published in recent years used similar theories adopted in the earlier research. The contributions to the less used theories mainly focused on qualitative and conceptual research, while the top three used theories were quantitative studies. This indicates that the less-used theories can be the new research directions for the RL studies. From the analysis of the authors, in contrast to the three used theories, few significant contributions have been made to a specific theory in the less used theories. In terms of data collection method, for IIT, most papers adopted primary data [Shaharudin et al., 2015; Dubey et al., 2017], and similarly in TPB, two papers both adopted the primary data [Brockhaus et al., 2016; Dixit and Badgaiyan, 2016]. It shows a deficiency of ST-incorporating research, with two quantitative [Kumar & Rahman, 2016; Nag et al., 2021] and two conceptual papers [Brockhaus et al., 2016; Kannan, 2018]. Furthermore, there is a lack of qualitative studies.

By systematically reviewing the literature, the total number of research on the topic incorporating management theories remains extremely insufficient. Moreover, few extended the theories. Most existing studies focused on SCM (e.g., GSCM, operation management). To RL, the existing research limited their focus on remanufacturing or recycling the disposal product, whereas few noticed the return and exchange logistics. Since the sector is gaining a greater importance, future research should pay closer attention to this research field via incorporating management theories, which, in turn, would benefit the development of the original theory.

Third, although some incorporated other factors into the management theories and developed a framework after examining their interrelationship, little contribution has been made to the theories themselves. Researchers can be more courageous in their approach by updating and broadening the theories explored. It also discovered that current research topics focus on product and material recycling, but few on product return and exchange logistics and consumers' purchase intentions on remanufactured products, where lies the direction of future research.

However, it is beyond the capabilities of this review to cover all the aspects and issues of this field due to the knowledge and resources constraints. Furthermore, the papers selected for this review were all from the WOS database, which could be another limitation. Furthermore, no similar review on the use of management theories has been published in the literature, making it difficult for this manuscript to compare the findings.

This paper aims to investigate the gap regarding the use and contribution of RL studies to organisational and to management theories and offer some insights into the RL study. The identified gaps and the corresponding future research directions are presented as follows. First, it confirms the concerns raised by the literature, although the number of RL and sustainability studies based on management theories has been increasing over the past decade. However, if comparing the number of organisational and management theories identified with the number of theories used in at least one paper, there is still a considerable gap. It is suggested that scholars involved in RL studies explore more connections between RL strategies and management theories in future research. Second, among the few management theories employed, TBL and CSF appeared to be more attractive for researchers in RL, and with respect to published articles, most of the articles were empirical studies conducted in the emerging market. Future studies could explore the reasons for this phenomenon.

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ORIGINAL PAPER

ADVANCING AGRIBUSINESS SUSTAINABILITY AND COMPETITIVENESS THROUGH LOGISTICS 4.0: A BIBLIOMETRIC AND SYSTEMATIC LITERATURE REVIEW

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ABSTRACT. Background: In the face of numerous sustainability challenges within global logistics operations, smart logistics, or Logistics 4.0, has emerged as a rapidly evolving field over the past decade. Situated within the broader context of Industry 4.0, Logistics 4.0 serves as a critical pillar for ensuring business sustainability by leveraging innovative and disruptive technological solutions. This study offers a novel and comprehensive analysis of the role of Logistics 4.0 in fostering business sustainability, with a particular focus on the agro-industrial sector.

Methods: Employing a bibliometric and content analysis approach, this research examines 56 publications from 2015 to 2021, sourced from Scopus, ScienceDirect, and Springer databases. The bibliometric research method incorporates joint keyword analysis using VOSviewer and is complemented by a content analysis of the selected articles. The bibliometric analysis uncovers a growing yet still nascent publication trend in this field.

Results: The study reveals that Logistics 4.0 plays a significant role in enhancing the sustainability of firms across various sectors, particularly within the agro-industrial sector. By harnessing digital technologies and innovative business models, Logistics 4.0 paves the way for creating competitive advantages for agro-industrial firms.

Conclusion: This research emphasizes the pivotal role of Logistics 4.0 in promoting sustainable and competitive growth in agribusiness, offering valuable insights for both academia and industry practitioners.

Keywords: logistics 4.0, agribusiness sustainability, agribusiness competitiveness, bibliometric analysis, systematic literature review.

INTRODUCTION

Logistics, as a concept, was initially related to military operations that included the transportation, supply, and maintenance of military equipment and personnel, with limited significance in the pre-1950s era. However, the scope of logistics expanded to include physical supply during the 1960s, giving rise to the term "business logistics" [Ballou, 2007]. Today, logistics pertains to the management of material and information flows within organizations, which involves overseeing the movement, storage, and related information of materials [Christopher, 2016]. The primary objective of logistics is to deliver finished products to customers with an appropriate level of service and quality at the lowest possible cost. Logistics has evolved into smart logistics or Logistics 4.0, which integrates technologies that automate logistics flows and enable real-time and near-

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real-time information availability [Winkelhaus and Grosse, 2020]. The benefits of Logistics 4.0 include timely delivery and supply, business agility, flexibility, responsiveness, and predictive analytics that can significantly reduce lead times, enhance quality, support environmental and social sustainability, and impact decision-making at different levels [Russell and Swanson, 2019; Tjahjono et al., 2021].

In the agribusiness sector, sustainability in agricultural production has become a critical issue for supply chains and their stakeholders [Satolo et al., 2020]. Agri-food supply chains encompass all productive and logistical measures from primary production to final product consumption and have become lengthier and more complex due to consistent international trade growth [Zupaniec et al., 2022; Frazzon et al., 2020]. Logistics activities' economic, environmental, and social impacts must be evaluated, and opportunities explored to make logistics productive and sustainable [Dey et al., 2011; Ahi and Searcy, 2013]. Logistics 4.0 has emerged as a solution to the sustainability challenges of firms in the agribusiness sector, with a focus on sustainable logistics solutions and addressing changing customer demands [Winkelhaus and Grosse, 2020]. This review aims to contribute to the existing knowledge on the role of Logistics 4.0 in agribusiness firms' performance, specifically within the context of Industry 4.0, focusing on sustainability and competitiveness concepts [Hardjomidjojo et al., 2022; Lin et al., 2018; Sharma et al., 2020]. It identifies key technologies, their applications, and effects on sustainability and competitiveness, highlighting the challenges and barriers agribusiness firms face when implementing Logistics 4.0 technologies [Bröring and Leker, J., 2021; Queiroz et al., 2020]. The review aims to promote a more comprehensive understanding of digital technologies' role in shaping a sustainable and resilient agri-food system for the future, including Logistics 4.0's potential impact on rural development, social equity, and environmental stewardship [Bronson and Knezevic, 2016; Frizzo-Barker et al., 2020]. The importance of empirical studies examining the real-world applications and impacts of Logistics 4.0 technologies in agribusiness settings is highlighted, including the influence of organizational culture, managerial practices, and the legal and regulatory environment on the adoption and diffusion of Logistics 4.0 technologies [Soto-Acosta and Cismaru, 2020; Raimundas et al., 2021]. Lastly, the review emphasizes the need to understand the potential implications of Logistics 4.0 adoption for small- and medium-sized enterprises (SMEs) in the agribusiness sector due to the distinct challenges they face [Gomes et al. 2018].

The expansion of logistics in the 1960s led to the emergence of the term "business logistics" to encompass physical supply and the management of material and information flows within organizations [Ballou, 2007; Christopher, 2016]. Today, logistics has evolved to address sustainability concerns and changing customer demands using emerging digital technologies, leading to the development of smart logistics or Logistics 4.0 [Winkelhaus and Grosse, 2020]. Logistics 4.0 integrates technologies that automate forward and reverse logistics flows, enabling real-time and near-real-time information availability and providing several benefits such as timely delivery and supply, agility, flexibility, responsiveness, and predictive analytics [Russell and Swanson, 2019].

Agri-food supply chains are considered critical for food safety, encompassing all logistical and productive measures from primary production to final product consumption [Codex Alimentarius Commission, 2016]. Due to the growth of international trade, agri-food supply chains have become more complex, involving intricate systems of numerous agents and interconnected processes [Bourlakis et al., 2014; Zupaniec et al., 2022]. Assessing the economic, environmental, and social impacts of logistics activities is crucial for ensuring supply chain sustainability [Dey et al., 2011; Ahi and Searcy, 2013]. Smart logistics, or Logistics 4.0, emerged in 2011 to address sustainability concerns and offer sustainable logistics solutions [Winkelhaus and Grosse, 2020].

Despite the potential benefits of Logistics 4.0 in agribusiness, there is a lack of literature regarding the influence of smart production practices on performance [Hardjomidjojo et al., 2022; Lin et al., 2018; Sharma et al., 2020]. To address this gap, this review aims to provide an understanding of the role of Logistics 4.0 in agribusiness sustainability and competitiveness within the context of Industry 4.0. By conducting a systematic literature review, the paper identifies the key technologies, their applications, and their effects on sustainability and competitiveness, while also highlighting the challenges and barriers faced by agribusiness firms in implementing Logistics 4.0 technologies [Büyüközkan and Göçer, 2018; Queiroz et al., 2020].

This review aims to serve as a foundation for future research on Logistics 4.0 in agribusiness, providing insights for practitioners and policymakers to develop effective strategies for adopting and integrating these technologies into their operations to achieve sustainable and competitive growth [Kamble et al., 2018; Akhtar et al., 2019]. Additionally, the paper promotes a comprehensive understanding of the role of digital technologies in shaping a sustainable and resilient agri-food system for the future, including its impact on rural development, social equity, and environmental stewardship [Bronson and Knezevic, 2016; Frizzo-Barker et al., 2020]. The review also emphasizes the need for more empirical studies examining the real-world applications and impacts of Logistics 4.0 technologies in agribusiness settings, as well as the potential implications for small- and medium-sized enterprises (SMEs) in the agribusiness sector [Gomes et al., 2018; Heras-Saizarbitoria et al., 2021]. Additionally, the influence of organizational culture, managerial practices, and the legal and regulatory environment on the adoption and diffusion of Logistics 4.0 technologies in agribusiness settings should also be further investigated [Soto-Acosta and Cismaru, 2020; Raimundas et al., 2021].

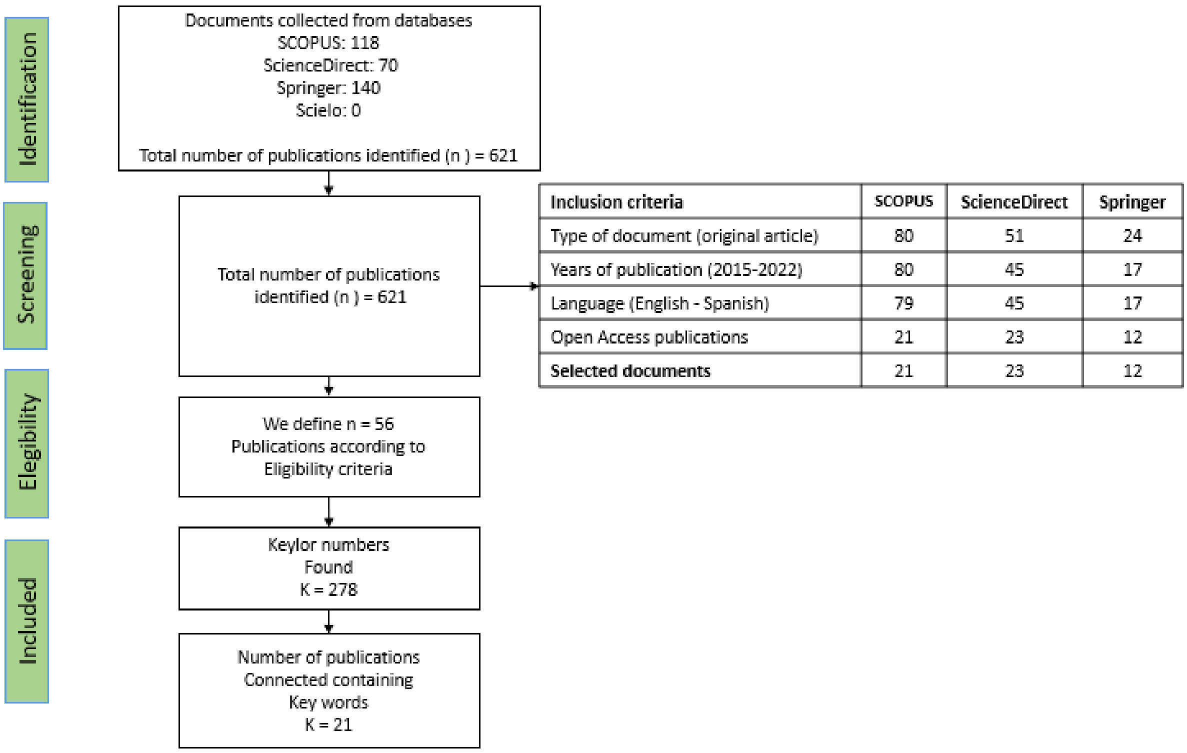
METHODOLOGY

A systematic literature review was employed to analyze the role of Logistics 4.0 as a fundamental pillar of sustainability and business competitiveness in the agribusiness sector. The systematic review methodology was chosen due to its replicability, transparency, and scientific rigor compared to traditional narrative reviews [Linnenluecke et al., 2019]. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to ensure the quality and transparency of the review process [Moher et al., 2009]. Asim and Sorooshian's [2019] research method was adopted to conduct the review

According to Asim and Asorooshian [2019], the descriptors, databases, eligibility criteria, and choice of documents were defined. This study used three databases as information sources: ScienceDirect, SCOPUS, and SpringerLink. The selection of ScienceDirect, SCOPUS, and SpringerLink databases for a systematic literature review of logistics 4.0 was likely based on their reputation and coverage of relevant academic journals and publications in the field. ScienceDirect is a well-known database that provides access to a large collection of academic journals, books, and conference proceedings in various fields of science, engineering, and technology. It is a part of the Elsevier publishing group and contains over 16 million articles from over 3,800 journals. SCOPUS is another highly regarded database that covers a wide range of scientific and technical disciplines, including the field of logistics. It is a product of Elsevier, and its content includes over 80 million records from over 25,000 journals, conference proceedings, and other sources. SpringerLink is a database that provides access to a vast collection of academic journals, books, and other publications in various fields of science, technology, and medicine. It is a part of the Springer Nature publishing group and contains over 13 million documents from over 8,000 journals. All three databases are well-established and widely used by researchers, and they have comprehensive coverage of relevant journals and publications in the field of logistics 4.0. By using these databases, researchers can access a large volume of peer-reviewed literature that is likely to be relevant to their research topic, and they can be confident that the sources are reputable and reliable. Additionally, these databases have advanced search functionalities that allow researchers to easily filter and identify relevant articles based on specific criteria such as publication date, language, and type of publication.

The search for relevant literature related to logistics 4.0 and its role in business sustainability in agribusiness was conducted by consulting documents published between 2015 and 2021. The search terms used were "Logistics 4.0," "Business Sustainability," and "Agribusiness." The inclusion criteria were 1) The title, abstract, and keywords of the publications were considered; 2) Publications written in English were considered; 3) Original articles were considered; 4) Open access publications were preferred. The database records were exported as comma-separated value (CSV) files. The search results, which met the eligibility criteria, yielded a total of 56 records in CSV format. The resulting Excel data were converted back to CSV for analysis in VOSviewer, a software tool used for creating bibliometric maps. The type of analysis used in VOSviewer was the co-occurrence and complete count method. When "all keywords" were used, 278 keywords were produced. The latter was considered for the analysis. The results from VOSviewer indicated that only 21 records were connected. Overall, the search strategy and inclusion criteria were designed to ensure that the literature reviewed was relevant and met the specific objectives of this study. The use of VOSviewer allowed for a visual representation of the bibliographic data and provided insight into the research landscape of logistics 4.0 and its role in business sustainability in agribusiness.

In accordance with the PRISMA guidelines, this study employed a rigorous selection process to identify relevant articles for inclusion in the review. The search was conducted across multiple databases, including Scopus, ScienceDirect, and Springer, using a specific set of keywords related to logistics 4.0 and agribusiness sustainability. A total of 21 articles were identified as meeting the inclusion criteria and were read in their entirety to ensure their relevance to the research question. The articles were then systematically analyzed to provide a comprehensive understanding of the role of logistics 4.0 in agribusiness sustainability and competitiveness. By adhering to the PRISMA guidelines, this study ensures transparency, replicability, and scientific rigor in the reporting of its results.



Inclusion criteria	SCOPUS	ScienceDirect	Springer
Type of document (original article)	80	51	24
Years of publication (2015-2022)	80	45	17
Language (English - Spanish)	79	45	17
Open Access publications	21	23	12
Selected documents	21	23	12

Fig. 1. PRISMA flow chart.

In various fields of study, bibliometric analysis is a commonly used method to analyze the scientific literature dataset [Daly et al., 2007a; Daly et al., 2007b]. VOSviewer, a software tool for creating, visualizing, and exploring maps based on network data [Van Eck and Waltman, 2020], was used in this study to analyze articles based on authors, keywords, institutions, and location. The co-authorship of the studies and the keywords were interpreted in terms of the concurrence they may present, as well as the connection between terms that exist in the articles. Content analysis was employed as a method to analyze the documents, as it provides a suitable tool for systematically extracting, analyzing, and interpreting data on the topic being addressed. Depending on the research question, content analysis can use qualitative and/or quantitative methods [Hsieh and Shannon, 2005].

To ensure the quality of the research, the evaluation of the qualitative data in this study is based on four criteria: credibility, transferability, dependability, and confirmability [Lincoln and Guba, 1985]. The study explored the concepts and principles of Logistics 4.0 and its role in the sustainability of agribusiness enterprises. The bibliographic framework was developed by exploring relevant academic and scientific publications, and the results can be used as a reference for future studies. The study was conducted using the PRISMA guidelines, which makes the process systematic, exhaustive, rigorous, replicable, and impartial [Moher et al., 2009]. This research is dependable because the search strings and eligibility criteria used in data collection will produce similar results if applied by other researchers.

RESULTS

Fifty-six papers meeting the inclusion criteria of this study were identified, with 41% from ScienceDirect, 37.5% from SCOPUS, and 21.5% from Springer. Most publications were from the year 2021, with 15 articles (Figure 2), indicating a growing interest in research on Logistics 4.0 and its role in the sustainability of agribusiness enterprises. Notably, during the first four years of the publication period considered [2015-2018], only 19 articles were published on this topic. This highlights a recent surge in attention and research efforts towards the application of Logistics 4.0 in agribusiness supply chains, as scholars and practitioners recognize its potential to drive business sustainability and competitiveness.

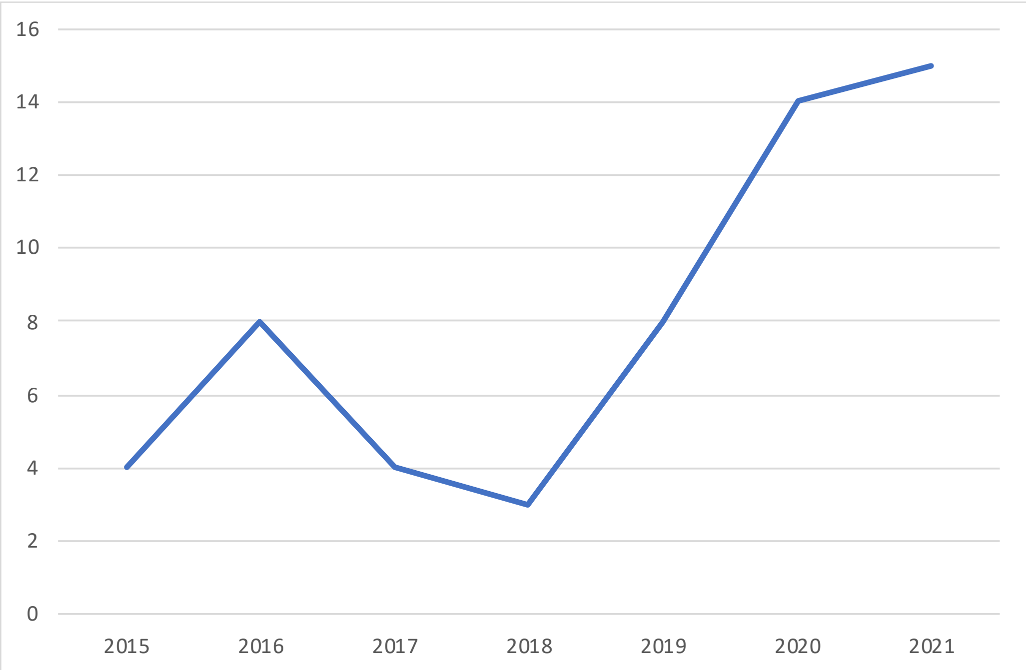


Fig. 2. *Publications by year.*

The analysis of the dataset revealed that Gunasekaran, Ivanov, and Liu were the most prolific authors, each with two publications. Among the journals, Sustainable (Switzerland) and Transportation Research Procedia had the highest number of publications, with five articles each. It was observed that the largest proportion of publications belong to the Business and Management field, accounting for 17.2%, followed by Engineering and Scientific Decisions, each with 14.1% of the publications. Overall, the results of the bibliometric analysis suggest that research on logistics 4.0 and its role in agribusiness sustainability is gaining attention in the academic community, as evidenced by the increasing number of publications in recent years. The analysis also reveals the main authors and journals contributing to this area of research, providing valuable insights for future studies.

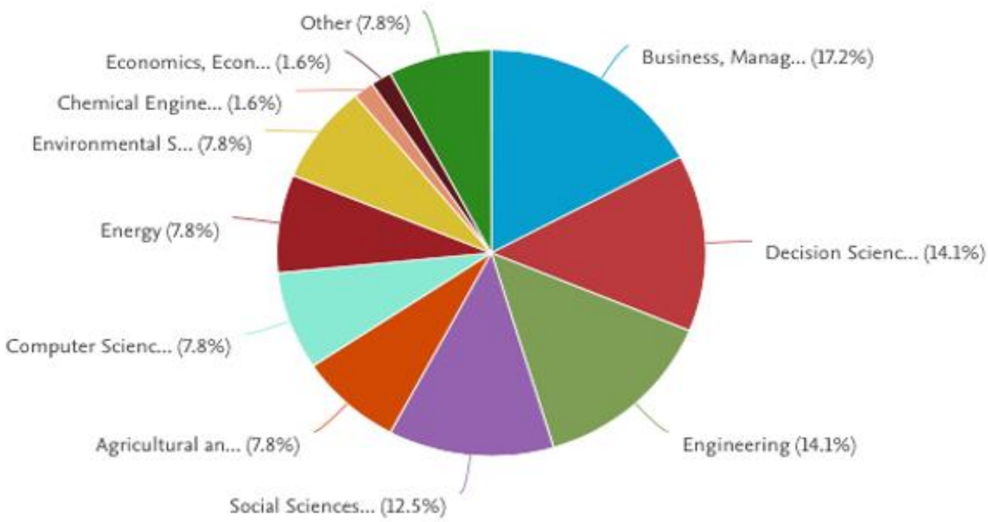


Fig 3. Publications by subject area.

A citation analysis was conducted to identify the most influential articles on the topic of logistics 4.0 and business sustainability in agribusiness. Out of the 56 articles included in this study, 7 were found to have a significant impact with a total of 539 citations. Supply chain and sustainability are critical areas of research, and several highly cited articles have contributed valuable insights to these fields. For instance, Ivanov et al. [2018] investigated the impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. This paper has received 269 citations since its publication, highlighting the relevance of digital technology in modern supply chain management. Another significant contribution is Ivanov's [2020] proposed viable supply chain model that integrates agility, resilience, and sustainability perspectives. The paper drew lessons from and offered insights beyond the COVID-19 pandemic, and it has been cited 105 times to date. Dubey et al. [2019] conducted an empirical investigation of data analytics capability and organizational flexibility as complements to supply chain resilience. This paper has received 77 citations since its publication, emphasizing the importance of data analytics in supply chain resilience. In a different study, Sharma et al. [2019] explored challenges and solutions for circular economy-driven sustainability practices in the food supply chain. The paper has been cited 32 times since its publication, highlighting the relevance of sustainability practices in the food industry. Todorovic et al. [2018] presented solutions for more sustainable distribution in short food supply chains, and the paper has received 24 citations since its publication. Sharma et al. [2020] analyzed agriculture supply chain risks and COVID-19 mitigation strategies, with implications for practitioners. This paper has been cited 16 times to date, demonstrating the relevance of the study during the COVID-19 pandemic. Lastly, Sun et al. [2020] studied the relationship between corporate social responsibility, co-creation, and green consumer loyalty, focusing on the importance of green banking initiatives in an emerging economy. This paper has also been cited 16 times since its publication, highlighting the importance of sustainability practices in the financial sector. Overall, these highly cited articles provide valuable insights into various supply chain and sustainability topics, including the impact of digital technology, the integration of agility, resilience, and sustainability perspectives, data analytics capability, circular economy-driven sustainability practices, and mitigation strategies for agriculture supply chain risks during the COVID-19 pandemic.

Using Multidimensional Scaling (MDS) techniques, VOSviewer creates a map of texts based on the gap or distance between them in terms of their meaning or similarity [Van Eck and Waltman, 2020]. These texts are represented as nodes or clusters in the map, and the connections between them can be presented in different ways, such as through network visualization, overlay visualization, and density visualization. In this study, VOSviewer was used to analyze 278 keywords related to logistics 4.0 and business sustainability in agribusiness, and only 21 items were found to be significant. The network visualization of the data tags yielded 4 clusters, 21 links, and 54 strong links. This approach helps to identify the main research themes and the relationships between them, providing a useful tool for researchers to identify gaps and opportunities for future research [Jamwal et al., 2022; van Eck et al., 20201].

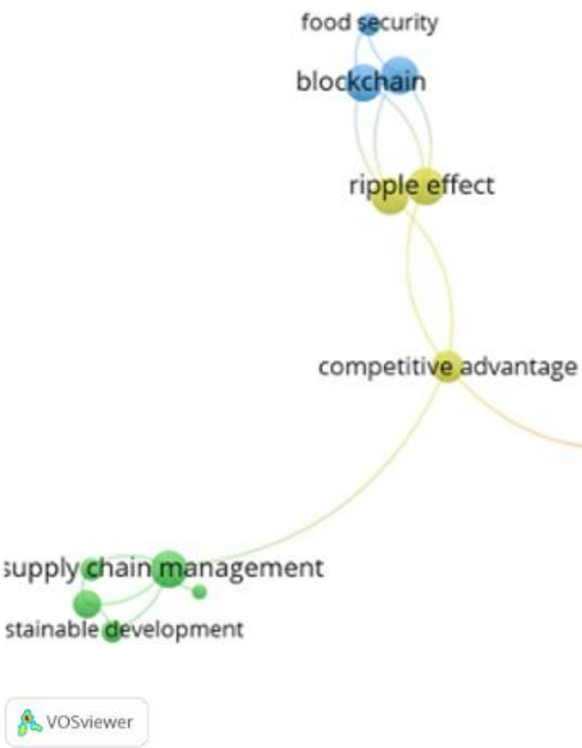


Fig. 4. *VOSviewer display network.*

Using VOSviewer, a cluster analysis of the 21 keywords revealed four distinct clusters, with 21 links and 54 strong links. The following analysis examines the keywords in each cluster with the highest number of occurrences and link strength: Cluster 1 (red) includes keywords related to the COVID-19 pandemic, food safety, quality, supply chain, and sustainability. The cluster reflects the growing interest in ensuring a safe and sustainable food supply chain during the pandemic, particularly in countries such as Greece. This cluster has 8 strong links, indicating a significant relationship between the keywords. Cluster 2 (green) includes keywords related to logistics, optimization, stakeholders, supply chain management, and sustainable development. This cluster highlights the importance of effective supply chain management and sustainable development practices for optimizing logistics and engaging stakeholders. The cluster has 20 strong links, indicating a strong interconnection between the keywords. Cluster 3 (blue) includes keywords related to blockchain, food security, and industry 4.0. This cluster reflects the growing interest in using blockchain and Industry 4.0 technologies to ensure food security and traceability. This cluster has 9 strong links, indicating a significant relationship between the keywords. Cluster 4 (yellow) includes keywords related to competitive advantage, ripple effect, and supply chain resilience. This cluster highlights the importance of supply chain resilience for achieving a competitive advantage and minimizing the ripple effect of disruptions. The cluster has 17 strong links, indicating a strong relationship between the keywords. Overall, the cluster analysis provides valuable insights into the research landscape of logistics 4.0 and its role in business sustainability in agribusiness. The identified clusters reflect the diverse interests and concerns of researchers in this field, including the impact of COVID-19 on the food supply chain, the importance of sustainable development practices and supply chain resilience, and the potential of blockchain and Industry 4.0 technologies.

In the visualization, the size of a label and circle of an item is determined by its frequency of occurrence. The higher the frequency of occurrence, the larger the label and circle of the item. In addition, the color of an item is determined by the cluster to which it belongs. The text elements or labels in the VOSviewer visualization represent the keywords that have multiple occurrences in the publications extracted from the review. A total of 21 keywords were found to have an occurrence greater than 2 times. Although the presence of COVID-19 as a keyword is notable due to the pandemic situation, it is worth noting that other keywords are relevant to the topic of study. For instance, the term "Industry 4.0" is found, which has led to the development of logistics 4.0. Additionally, the terms "sustainable development" and "supply chain management" are also present. In terms of the agro-industrial sector, words related to "food safety" and "circular economy" are found, indicating that there is still room for further research on these topics in relation to logistics 4.0 and business sustainability in agribusiness.

DISCUSSION

In a content analysis of 56 publications related to sustainable development and agribusiness, digital technologies and mathematical models such as data analytics, blockchain, IoT, robust optimization, and mixed linear programming were found to be increasingly utilized to improve supply chain resilience, transparency, and sustainability [Dubey et al., 2019; Kayikci et al., 2020; Sundarakani et al., 2020; Yadav et al., 2020]. Co-creation and AgriFood-Tech were also identified as emerging trends that are contributing to the growth and sustainability of the agribusiness sector [Heberli et al., 2019; Vlachopolou et al., 2021]. The Supply Chain Management Dashboard was shown to be an effective tool in facilitating collaboration and improving decision-making in supply chain management [Sithole et al., 2016].

Logistics 4.0 presents an opportunity for improving the distribution of short food supply chains and aligning with contemporary logistics trends, sustainability, and the new digital era [Todorovic et al., 2018]. However, to achieve the full potential of Logistics 4.0, optimized planning, incentive alignment, and cross-company collaboration are needed [Lee and Shen, 2020]. The Belt and Road Initiative (BRI) offers significant opportunities for improving supply chain logistics, but requires new work processes and technologies, incentive alignment, cross-company collaboration, and optimized planning [Lee and Shen, 2020]. Linn and Maenhout [2019] emphasize the importance of including Logistics 4.0 in strengthening business models in agro-industrial sectors such as rice, which exhibit low technical efficiency and very low chain performance.

To mitigate the various risks that agribusiness supply chains face, Industry 4.0 technologies, supply chain collaboration, and shared responsibility have been suggested

[Sharma et al., 2020; Jamwal et al., 2021, 2022]. Decentralized production presents challenges to the cold supply chain, but short-distance transportation and modern marketing methods offer potential solutions [Almena et al., 2020; Zhou et al., 2020]. To increase farmers' income and social capital, strengthening the supply chain and competitive advantage have been recommended [Karim et al., 2020; Jamwal et al., 2021].

In terms of supply chain viability, sustainability should encompass environmental soundness, social equity, and economic viability [Borsellino et al., 2016]. Value Co-creation, AgriFood-Tech, Supply Chain Management Dashboard, and Routination are models that have been applied to enhance supply chain viability [Ivanov, 2020; Jamwal et al., 2022]. Value co-creation enables active participation, mutual learning, and direct influence through a dialogic process between the company and the customer [Heberli et al., 2019]. AgriFood-Tech business models contribute to the growth and sustainability of the agribusiness sector by fostering innovation, accelerating structural change, enhancing productivity, and introducing new products and services to the market through the implementation of digital environments [Vlachopoulou et al., 2021]. The Supply Chain Management Dashboard promotes integrated supply chain management by facilitating collaboration and supporting executive decision-making, thereby increasing transparency, operational efficiency, cost-effectiveness, and food assistance delivery to vulnerable populations [Sithole et al., 2016]. Routinization enables firms to reconfigure their knowledge base, providing insight into the impact on internal and farm operations performance [Heberli et al., 2019].

Digital technologies such as Industry 4.0 enhance demand responsiveness, capacity flexibility waste, enhancing traceability, and increasing transparency and accountability, as emphasized by Kayikci et al. [2020]. Big Data analytics can help firms identify trends, predict demand, and optimize supply chain operations, as highlighted by Dubey et al. [2019]. Simulation models can help in evaluating alternative scenarios, identifying bottlenecks and optimizing resource utilization, as noted by Jamwal et al. [2022].

Development in agribusiness requires the application of innovative technologies and practices that enhance transparency, supply chain resilience, and economic, social, and environmental sustainability. The literature review highlights the potential of digital technologies such as Industry 4.0, IoT, Big Data, and Blockchain, and mathematical models such as robust optimization and mixed linear programming in enhancing supply chain sustainability. Additionally, co-creation and AgriFood-Tech are emerging trends that contribute to the growth and sustainability of the agribusiness sector. The Belt and Road Initiative presents opportunities for improving supply chain logistics, but requires new work processes and technologies, incentive alignment, cross-company collaboration, and optimized planning to realize its full potential. Finally, Logistics 4.0 offers significant opportunities for improving the distribution of short food supply chains and strengthening business models in the agro-industrial sector, but corresponding solutions are needed to enable firms to improve their operational performance and create economic value while considering factors such as optimized planning, incentive alignment, and cross-company collaboration.

CONCLUSIONS

Logistics 4.0 represents a paradigm shift in supply chain management, driven by the integration of material, information, and financial flows through automation and digital technologies. This evolution enables supply chains to become faster, more accurate, and more efficient in areas such as information exchange, physical flow, planning activities, performance, order management, inventory control, and cost reduction. The transition to Logistics 4.0 requires a progressive transformation process that incorporates environmental, social, and societal dimensions. This shift plays a crucial role in enhancing the sustainability of firms in general and is particularly impactful in the agribusiness sector.

The adoption of digital technologies and innovative business models through Logistics 4.0 creates a significant competitive advantage for agribusiness firms. Key components of Logistics 4.0 include data analysis capabilities, blockchain, robust optimization and mixed linear programming, the Internet of Things, AgriFood-Tech, and routination, which serve to improve logistical processes. Additionally, digital technologies can be utilized to assess and mitigate various risks in agri-food production. This research provides valuable insights for organizations and practitioners, enhancing their understanding of Logistics 4.0 and its implications for business sustainability in the agribusiness sector. To the best of our knowledge, this is the first publication to examine the role of Logistics 4.0 in fostering sustainable business development, specifically within the agribusiness sector.

As an emerging research area, Logistics 4.0 has the potential to be applied across various industries and sectors. Future studies should focus on empirical research that demonstrates the positive outcomes of implementing digital technologies in the supply chains of diverse agribusiness firms. Additionally, qualitative studies engaging organizational leaders can be used to investigate the extent of technology development in logistical processes. It is also important to measure the adaptability and progress of firms in adopting digital technologies within the framework of Logistics 4.0.

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ORIGINAL PAPER

FUZZY EVALUATION METHOD FOR ENVIRONMENTAL FACTORS AFFECTING A MOBILE ROBOT'S SENSOR SYSTEM IN VIEW OF DESIGN FOR LOGISTICS

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ABSTRACT. Background: The paper is devoted to mobile robot design problems with a focus on exteroceptive sensor systems for operation in a mixed environment (indoor with outdoor possibility). With a view to the design for logistics, the important concerns are, among others, minimization of the number of parts, reduction of weight, and reduction of dimensions. One of the challenges that arise here is the consideration of environmental factors, which vary among different application systems. It is necessary to reach a compromise between operational requirements and costs involved. Therefore, the relevance of the environmental factors should be evaluated to divide them into those that should be addressed and those that can be ignored. This will translate into the selection of sensors in sufficient quantity to provide the requirements without excessiveness.

Methods: We propose a novel three-stage method for assessing the relevance of environmental factors using fuzzy logic with occurrence, recovery, and impact level consideration. We take into account the impact level of each factor on the entire sensor system, restoration of functions lost completely or partially as a result of the factor (recovery), and the frequency of factor occurrence.

Results: The identified environmental factors, evaluated in term of their relevance are hierarchized from the most to the least relevant. The application of the method is presented on the basis of an autonomous forklift for indoor and outdoor use.

Conclusions: Based on the proposed method, it is possible to design a sensor system with consideration of any operation environment. The three-criteria method allows evaluation of any factor influencing sensor system on a five-point scale, both in terms of occurrence and severity (understood as impact level effect and recovery time). By evaluating the factors and thus prioritizing them using our method, only the most important factors from the designer's point of view can be taken into account. This can translate into minimizing the number of sensors and thus cost reduction and shorter implementation time.

Keywords: Design for Logistics, mobile robot, sensor system design, fuzzy set theory, mixed environment

INTRODUCTION

Design for Excellence (DfX) is a methodology that engages versatile groups with knowledge about different phases of the product life cycle to advise during the design phase. Issues are assessed here beyond base functionality understood as meeting customer expectations [Tulkoff and Caswell 2021]. The multidisciplinary nature of this approach is reflected in its key elements, such as Design for Manufacturing, Design for Reliability, Design for Environment, or Design for Quality. A part of DfX is also Design for Logistics (DfL). The concept was first mentioned in 1990, but it's assumptions are still relevant today. Following DfL, design actions should be aimed, among others, at minimization of the number of parts, use of standard parts, reduction of product dimensions and weight, and minimization of packaging use [Bielecki et al. 2021]. These activities are particularly important in products being developed in the era of Industry 4.0, which are often associated with high financial investments.

One of the products specific to Industry 4.0 are mobile robots [Freund and Al-majeed 2021;

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Żuchowski 2022] with varying degrees of autonomy and different industrial and service applications. When designing mobile robots, it is necessary to consider a number of factors that negatively affect proper operation and safety. In a limited, closed, structured area such as a warehouse, mostly static and dynamic obstacles (people) [Norton and Yanco 2016], overhanging infrastructure [Hedenberg and Åstrand 2016], and lighting [Y. Li and Birchfield 2010] can be problematic. In contrast, the outdoor environment has many uncertain, changing conditions that are difficult to predict, which are mainly weather (rain, snow, and low temperatures) [Vargas et al. 2021] and terrain features (uneven surfaces, plants, and unpredictable objects) [Ward and Iagnemma 2008]. It was also noticed that there is a clear division of the research according to the application area of the mobile robots under study. It was observed that solutions dedicated to the indoor environment are less demanding in terms of navigation, localization, and obstacle detection. It is associated with a known, mostly predictable environment and its conditions. The main challenge and source of uncertainty in this case is people, considered as dynamic obstacles. Therefore, the total cost of sensors in indoor-only applications is frequently lower than the total cost of sensors in outdoor applications, which must meet higher requirements. In relation to the above, environmental factors are unavoidable when considering the sensor system of mobile robots. The sensor system needs to be considered with relation to proprioceptive (measuring the robot's state) and exteroceptive sensors (measuring the environment's state). Our work is limited only to the exteroceptive sensors.

The design and later implementation of a mobile robot operating indoors and/or outdoors determine the need to study the sensor system with reference to environmental factors. Sensors have limitations resulting from their operation under various environmental factors. Regardless of the application area (only indoors, only outdoor, or indoors and outdoors), the number of factors interfering with sensor operation should be considered while designing a sensor system. The multiplicity of these factors makes it necessary to prioritize them depending on their influence on the tasks performed by the object.

Among the tasks related to the problem of designing the sensor system of mobile robots, issues such as sensor fusion, sensor placement, sensor selection, and sensor testing are considered. There is also a broad group of studies addressing sensor signal processing, but these papers were not included in the literature review due to their indirect relationship to the sensor system design considered at the level of our study. Table 1 presents selected works that correspond to the above mentioned issues. Papers from the sensor selection group will be discussed in detail because of their strong connection to the problem we are considering and the need to outline the research gap later.

In the case of the sensor selection problem, there are many papers available in the literature as a form of comparative analysis. Attention is focused here on the parameters of sensors generally available in their technical specifications and the limitations due to various factors. In [Vargas et al. 2021], the effects of precipitation, fog, humidity, thunder, sun glint, dust storm on LiDAR, RADAR, camera, and ultrasonic scanner are discussed in detail. Available research results for each of the factors indicated have been summarized. The paper provides a descriptive comparison of various sensors by pointing out their advantages and limitations. A similar but more general comparison of the sensors is presented in [Rosique et al. 2019], where cameras, lidar, RADAR, and ultrasonic sensor were compared based on spider charts in the context of FOV, range, accuracy, frame rate, resolution, colour perception, size, weather affections, maintenance, visibility, and price. [Singh and Nagla 2020] focused on selecting a sensor for autonomous navigation. The proposed methodology consisting of 12 layers starts with environment characteristics, which can negatively or positively influence considered laser sensor, vision sensor, or sonar/radar. In [Yeong et al. 2021], camera, LiDAR, and Radar were compared on a three-level scale that started from operating competently under the specific factor then to performing reasonably well, and finally to the worst: not operating well under the specific factor. A common feature of the works cited is the consideration of selected types of sensors with reference to selected factors.

Table 1. Summary of selected papers concerning different problems with sensor system designing

Sensor system design problem	Ref.	Brief Summary (e.g., considered sensors, benchmarks, indicators, methods classification)
sensor selection	[Vargas et al. 2021]	Criteria: range, resolution, weather conditions affect, lightning conditions affect, speed detection, distance detection, interference susceptibility, size Sensors: LiDAR, RADAR, camera, ultrasonic
	[Singh and Nagla 2020]	Criteria: environment-connected (indoor, outdoor, harsh environment conditions, structured/unstructured environment, or geometrical constraints), navigation characteristics (accuracy, FOV, level of autonomy, 2D/3D navigation, computational load, speed), navigation application (aerial, ground, underwater) Sensors: laser sensor, vision sensor, sonar/radar
	[Rosique et al. 2019]	Criteria: FOV, range, accuracy, frame rate, resolution, colour perception, size, weather affections, maintenance, visibility, price Sensors: cameras, lidar, RADAR, ultrasonic sensor
	[Yeong et al. 2021]	Criteria: range, resolution, distance accuracy, velocity, color perception, object detection, object classification, lane detection, obstacle edge detection, illumination conditions, weather conditions Sensors: camera, LiDAR, Radar
sensor placement	[Kim and Park 2020]	Indicator: lidar occupancy rate (LO %) Sensor: 3D lidar
	[Nikolaidis et al. 2009]	Indicators: weighted ratio of visible to total area, minimum number of cameras Sensors: cameras
	[Dey et al. 2021]	Indicators: cost function, longitudinal position error, lateral position error, object occlusion rate, velocity uncertainty, rate of late detection, positive and negative lane detection rate, positive object detection rate Sensors: radar, camera
	[Keyes et al. 2006]	Indicators: total time on task, number of collisions Sensors: cameras
sensor fusion	[Qu et al. 2021]	multi-sensor fusion methods for navigation: visual sensor-dominant navigation, lidar dominant navigation, UWB combined wth IMU and others
	[Fayyad et al. 2020]	deep learning sensor fusion methods for perception, localization and mapping
	[Kocić et al. 2018]	sensor fusion methods for: 3D object detection (camera+lidar), occupancy grid mapping (cameras+lidar), moving object detection and tracking (camera, radar and lidar)
	[Q. Li et al. 2020]	different localization approaches with the use of multiple sensors: GNSS-based localization, GNSS + IMU localization, Lidar odometry (LOAM), NDT-based localization, NDT + IMU
sensor testing	[Tang et al. 2020]	Indicators: object detection success/failure under rainy and sunny weather Sensors: lidar, camera
	[Heinold et al. 2021]	sensors robustness verification with the Scenario-Based Noise Deployment involving assumptions of Quality Function Deployment (QFD)
	[El-Hassan 2020]	Indicators: lane detection, object detection, and collision avoidance with yes/no Sensors: lidar, ultrasonic sensor, camera, color sensor, microcontroller
	[Bijelic et al. 2018]	Indicators:: visibility, entropy (information content in the sensor stream), depth of target, contrast under foggy conditions Sensors: lidar, camera, gated camera

Another problem is sensor placement. The available work mostly focuses on the arrangement of homogeneous sensors as in [Kim and Park 2020], where the focus was on lidar. The placement was studied based on the occupancy rate and aimed at determining lidar's optimal position and orientation to maximize data density, reduce dead zone, and improve point cloud resolution.

The use of only one sensor is insufficient; hence, multi-sensor implementation requires consideration of sensor fusion, which has been comprehensively discussed in [Galar and Kumar 2017].

On the other hand, a separate group of papers deals with sensor testing, in which research is conducted on pre-selected sets of sensors, and various methods dedicated to object detection, navigation, and localization are proposed.

Environmental factors in the context of their influence on the sensor system have already been extensively studied in recent years, as evidenced by numerous review publications. The most commonly used exteroceptive sensors (lidar, radar, camera, and ultrasonic) are presented in terms of weather conditions, rough terrain, dynamic obstacles, or problematic infrastructure (overhanging elements, reflective surfaces). A specific type of sensor is considered with reference to a variety of factors. There may be more or less factors depending on the system's characteristics under study. The more factors identified and sensor parameters considered, the more complex the problem becomes. On the one hand, it is difficult to select sensors that perform well under given environmental factors and, on the other hand, to include all identified factors in the experiments. Research available in the literature addresses selected sensor types. Methods related to environmental factors are lacking. Instead of referring the sensor parameters to the impact of the environmental factor, it is worth taking the opposite approach. The identified environmental factor occurring in the system under study should be addressed by considering the sensor system as a whole, not as individual elements. In addition to the impact of the factor (already described in the literature), the frequency of occurrence and the system's recovery time must also be determined. This will allow the identified environmental factors to be assessed for relevance, i.e., it will be possible to identify those necessary for consideration and those to be ignored. The aim of this paper is to evaluate the relevance of environmental factors affecting the performance of mobile robot's exteroceptive sensors.

The main contributions of this study are the following:

- We have proposed a three-stage fuzzy evaluation method for environmental factors affecting exteroceptive sensors of a mobile robot.
- We have defined and used three criteria (occurrence, recovery, impact level) to assess the relevance of the identified environmental factors.
- In contrast to the available studies, we have evaluated environmental factors with relation to the entire sensor system, and we did not consider each sensor separately.
- We considered the DfL in the context of mobile robot design.

A FUZZY EVALUATION METHOD

To the best of our knowledge, there is a lack of methods in the literature to support sensor system design in the context of environmental factors. Literature shows that predesigned sensor systems or its elements are tested under the influence of selected environmental factors. However, each system where a mobile robot is implemented will be characterized by different factors, so different solutions will be used for different systems. A mobile robot is designed by a group of people with knowledge mainly in the field of automation, robotics, and electronics. Therefore, it can be said that a group of experts from various fields makes decisions about the design of the whole object and consequently about its individual systems such as the sensor system discussed in this article.

When considering environmental factors, it is necessary to identify those relevant to the system under study. Determining the relevance of environmental factors is critical to avoid overprotecting the object in the form of an excessive number of sensors. The determination of relevance based on the classical logic of 0-1, meaning relevant or not relevant, is insufficient and difficult to determine. Each expert may consider relevance differently, and each factor may be more or less relevant. Additionally, when interviewing experts, one can get answers such as very high relevance, medium relevance, etc. Traditional quantitative methods do not account for the indicated uncertainty associated with human behavior in the decision-making process [Blanco-Mesa et al. 2017]. Classical 0-1 logic is not applicable here. Therefore, we decided to use fuzzy logic to model logical reasoning and to encode expert opinions based on experience and knowledge of the system.

In view of the above, fuzzy logic [Chen and Pham n.d.] will succeed in the problem of assessing the relevance of environmental factors in relation to the sensor system. When assessing the relevance, it is necessary to define the criteria to be taken into account. In our method, we propose three criteria: Recovery, Occurrence and Impact level. Finally, knowing the Recovery, Occurence, and Impact level, it will be possible to determine the Factor relevance, which should be referred to the designed sensor system.

A scheme of the proposed method for evaluating the relevance of environmental factors affecting the exteroceptive sensors is shown in Figure 1.

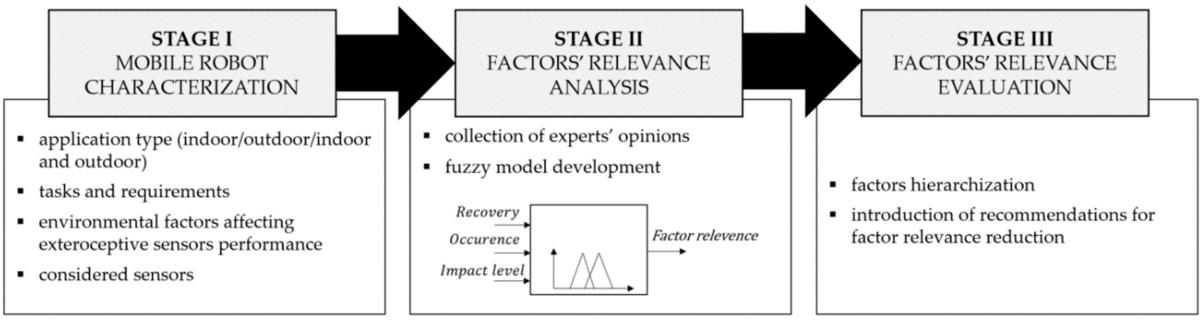


Fig. 1. A general scheme of the proposed fuzzy evaluation method

There are three stages in the proposed method: mobile robot characterization, factors' relevance analysis, and factors' relevance evaluation.

Stage I. Mobile robot characterization

A sensor system is one of the many systems of a mobile robot. The selection of its elements is connected with requirements and tasks, environmental factors occurring in the environment, and type of application with consideration of safety and costs. The type of application, being either indoor-only, outdoor-only, or mixed, significantly affects the reduction or increase in the number of environmental factors, which may interfere with the sensors. Among the tasks and requirements to be fulfilled by the object, one should, for example, take into account the assumed performance, type of transported load, and safety in the context of human presence in the working area. When examining the set of sensors under consideration, a key issue is the environmental factors that depend on the object's application system. These factors may interfere with the operation of the object to a greater or lesser extent. Therefore, it is reasonable to assess them in terms of relevance. The output of the first stage are the identified environmental factors specific to the system under study and description of the mobile robot in the context of its requirements, type of application, and the considered sensor system concept.

Stage II. Factors' relevance analysis

Identified environmental factors negatively affecting sensor system performance are considered based on three criteria: recovery, occurrence, and impact level using fuzzy logic. In this way we take into account the impact level of the factor, restoration of functions lost completely or partially as a result of the factor (recovery), and the frequency of factor occurrence. Characteristics of the fuzzy model with the indication of the input and output variables and the types of membership functions used are presented in the Table 2.

Table 2. Characteristics of the fuzzy model

Linguistic variable name	Linguistic variable type	Membership function name	Membership function type
Occurrence	input	very unlikely unlikely possible likely very likely	trapezoidal triangle triangle triangle trapezoidal
Recovery	input	very short short average long very long	trapezoidal triangle triangle triangle trapezoidal
Impact level	input	negligible moderate significant	trapezoidal triangle trapezoidal
Factor relevance	output	very low low average high very high	trapezoidal triangle triangle triangle trapezoidal

Recovery (Re) is the time required for the system to return to a fully operational state without maintenance actions. The membership functions for the linguistic variable Recovery are shown in Figure 2. Five membership functions describing the duration of recovery were assigned to this variable as very short, short, average, long, and very long. We propose considering the variable in minutes, so the Recovery can be rated in general on a scale of 0 to positive infinity. However, determining the parameters of the functions adequate for the system under study will limit this range.

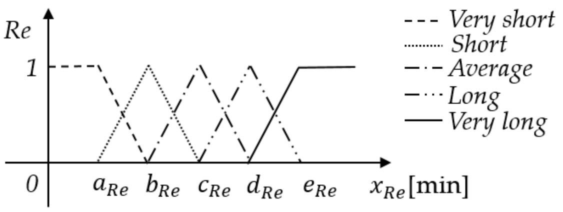


Fig. 2. Membership functions of the linguistic variable Recovery

Occurrence (Oc) determines the frequency of occurrence of an environmental factor. The climate in the studied area determines it (e.g., frequency of precipitation, sunny days, frosty days) and the characteristics of the studied system (e.g., type of ground resulting in lower/ higher dustiness). It is related to the probability of occurrence of a factor as the ratio of days with an observable factor and all days. The use of probability determines the Occurence range from 0 to 1. The membership functions for the linguistic variable Occurrence are shown in Figure 3.

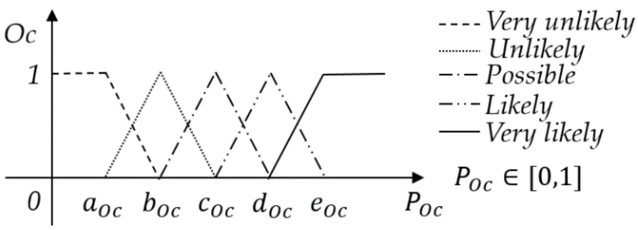


Fig. 3. Membership functions of the linguistic variable Occurrence

Impact level (Il) addresses the effect of the environmental factor under consideration on the sensor system. A three-level scale describes this criterion:

1. Negligible – the effects of the factor cause a limitation in the operation of one of the sensors, but in terms of the entire system, there is no loss of operational reliability.

2. Moderate – the influence of the factor is significant for the sensor system and causes its partial malfunction, e.g.: by limiting the field of view of the sensors, affecting the whole system.

3. Significant – the impact of the factor makes it impossible to perform the basic tasks defined for the system (e.g.: loss of safety as a consequence of, for example, loss of human detection capability).

The membership functions for the linguistic variable are shown in Figure 4.

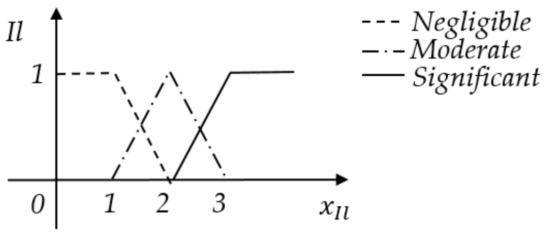


Fig. 4. Membership functions of the linguistic variable Impact level

Based on fuzzy input parameters (Recovery, Occurrence, Impact level) and inference rules, it is possible to provide for each of the identified environmental factors its Factor relevance with a range from 0 to 6. Membership functions for a linguistic variable Factor relevance are shown in Figure 5.

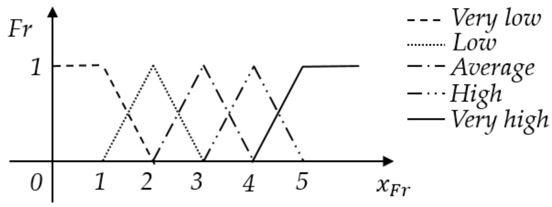


Fig. 5. Membership functions of the linguistic variable Factor relevance

Defuzzification of Factor relevance (output variable) is performed after the application of the center of gravity method. Fuzzy value of Factor relevance is transformed into crisp one.

Stage III. Factors' relevance evaluation

Having defined the Factor relevance, it is possible to prioritize the examined environmental factors and on its basis, to introduce actions for reducing this relevance. It is desirable to achieve the lowest possible Factor relevance for a given factor. However, its acceptable value depends on the system's specifics and the designer's assumptions. For some, relevance at the upper range of values will signal the need to adjust the system, and for others, it will be at the lower range. If an unacceptable factor relevance is obtained, it is necessary to modify the sensor system concept under investigation.

METHOD APPLICATION BASED ON AUTONOMOUS FORKLIFT

Stage I. Mobile robot characterization

According to the described stages of our method, initially (within stage I) it is necessary to characterize the analyzed mobile robot. The application of the proposed method will be demonstrated using an example of an autonomous forklift being developed as part of a research project POIR.01.01.01-00-0691/19 funded by the Polish National Centre for Research and Development. The project's theme focuses on the development of an autonomous forklift performing transport tasks within a mixed work environment, mostly indoor, but with outside possibility. The project's objectives included the selection of sensors, enabling the implementation of transport tasks under the described conditions while maintaining the maximum level of safety. Among the tested exteroceptive sensors of the forklift are three Intel Realsense 435i 3D cameras and three SICK S300 Advanced laser safety scanners. The sensors are to allow localization, navigation, and detection of objects (obstacles and cargo to be picked up). One of the sensor arrangements considered is placing two scanners and two cameras at the front of the forklift (at the contact points between the body surface and the side surface and at the inner mast and carriage, respectively) and one scanner and one camera at the back. Despite the need to consider the operation of the object outdoors, we consider a laser scanner dedicated (according to the specifications) to indoor applications. Thus, we want to test the limitations of such a solution in the system under study, which will reduce costs if acceptable results are achieved.

An autonomous forklift performing indoor and outdoor transportation tasks faces several disruptive factors. We can divide these factors based on the level of uncertainty into controlled and uncontrolled. Within the first group (controlled), we distinguish factors resulting directly from the system's characteristics. These include: the changing topology of the maneuvering area, diversity of transport units, lack of characteristic landmarks (empty yard). The second group (uncontrolled) includes all factors of random nature, including: weather conditions (fog, harsh lighting, operation in the absence of light, precipitation, changing temperature, etc.) and the impact of the system environment (e.g.: dust resulting from the operation of other equipment).

The fuzzy evaluation method will be applied to the second group of factors. The following factors were evaluated: condensation, low temperature (below zero), fog, and dustiness.

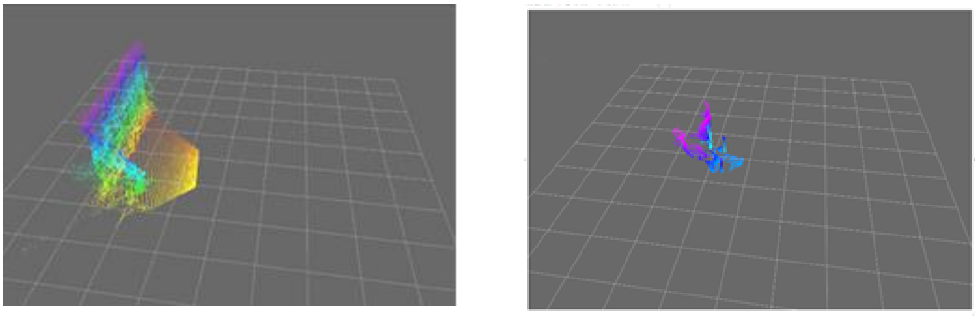
Stage II. Factors' relevance analysis

For the identified factors, within Stage II, a factor relevance analysis is performed. Expert opinion supported by dust and fog tests of varying severity and climate chamber tests were used for relevance analysis.

The tests in the climate chamber aimed to verify the selection of sensors for the implementation in outdoor conditions. The impact of temperature and humidity changes on the operation of scanners and cameras was analyzed. The climate chamber used in this study has the following parameters:

- dimensions 5,2x5x4 m
- temperature range from – 20 °C to + 50 °C
- humidity range from 5 to 20 g/m3 (above 10 °C).

Sensors placed in the climate chamber lowered their temperature to ambient temperature (verification based on measurements from a thermal camera). We only verified the temperature of the housing, we did not take measurements inside the device. Despite the temperature drop, the sensors were working properly. We could not read the differences in signals coming from scanners of different temperatures. However, as expected, the problem turned out to be each time the device was taken out of the chamber. As a result of differences in the temperature of the surroundings and the measuring equipment, condensation of water vapor on the sensor's surface occurred every time. Water vapor condensing on the surface of the sensors made measurement impossible. Both the cameras and the scanners lost their proper operation capabilities. It can be seen in the 3D visualization produced by using Rviz (Figure 6). The time of device inoperability lasted until the device was warmed up to room temperature and the water evaporated. At a room temperature of 21°C, the time required for full recovery was over 15 minutes. The measurements obtained clearly indicate that the transition of the forklift between indoor and outdoor environments is an important issue.



a) b)

Fig. 6. View from the sensor before and after taking it out of the climate chamber: a) correct 3D camera view b) interfered 3D camera view

In addition to verifying the effects of temperature on sensor performance, the effects of dust and fog were also analyzed. A fog generation device with efficiency 215 m3/min was used to study the effect of fog. It was applied in a room of 90 m3. Additionally, as part of our research, we wanted to verify whether and to what extent dust grain size affects sensor performance. Another goal was to verify what level of dustiness is the limiting level for the performance of individual sensors.

The first test was under fog conditions. After only 20 seconds of operation, the amount of fog generated (71.6 m3) limited the operation of the safety system based on the SICK S300 Advanced scanner to an area with a radius of 500 mm. Tests performed to verify the effect of grain size on scanner performance showed that regardless of grain size, a 100mm stream fed at a velocity of 2 to 10 g/s was identified by the scanner as a solid obstacle. In contrast, a significant result was observed as an indirect effect of the dusting. Dust falling to the floor rose uniformly in all directions after a few seconds of testing; even though the dust was practically invisible, it caused a clear performance limitation of the scanner. Grain size did not matter when the stream was dosed in front of the scanner, but it did affect the particle persistence time in the air. The test was carried out in a room, so it is difficult to assess the results of the measurements in relation to conditions occurring outside. However, dust, for example, which can appear in summer, raised by vehicles working in the surroundings of the forklift may cause interference with the scanner.

Taking into account the tests performed and the expert opinions obtained, the parameters of the membership function for the linguistic variables Oc, Il, Re, and Fr were adopted, which are shown in Table 3.

For the assumed parameters of the membership function and inference rules, plots of the dependence of the output variable on the studied input variables were obtained (Figure 7).

Table 3. Definition of the linguistic variables for the case under consideration

Linguistic variable name	Membership function name	Membership function parameters	Supporting research for parameter estimation
Occurrence	very unlikely unlikely possible likely very likely	[0, 0, 0.04, 0.08] [0.04, 0.08, 0.12] [0.08, 0.12, 0.16] [0.12, 0.16, 0.2] [0.16, 0.2, 1, 1]	analysis of meteorological conditions over recent years
Recovery	very short short average long very long	[0, 0, 1, 2] [1, 2, 3] [2, 3, 4] [3, 4, 5] [4, 5, 6, 6]	testing in the climate chamber, simulation of dust and fog
Impact level	negligible moderate significant	[0, 0, 1, 2] [1, 2, 3] [2, 3, 4, 4]	
Factor relevance	very low low average high very high	[0, 0, 1, 2] [1, 2, 3] [2, 3, 4] [3, 4, 5] [4, 5, 6, 6]	

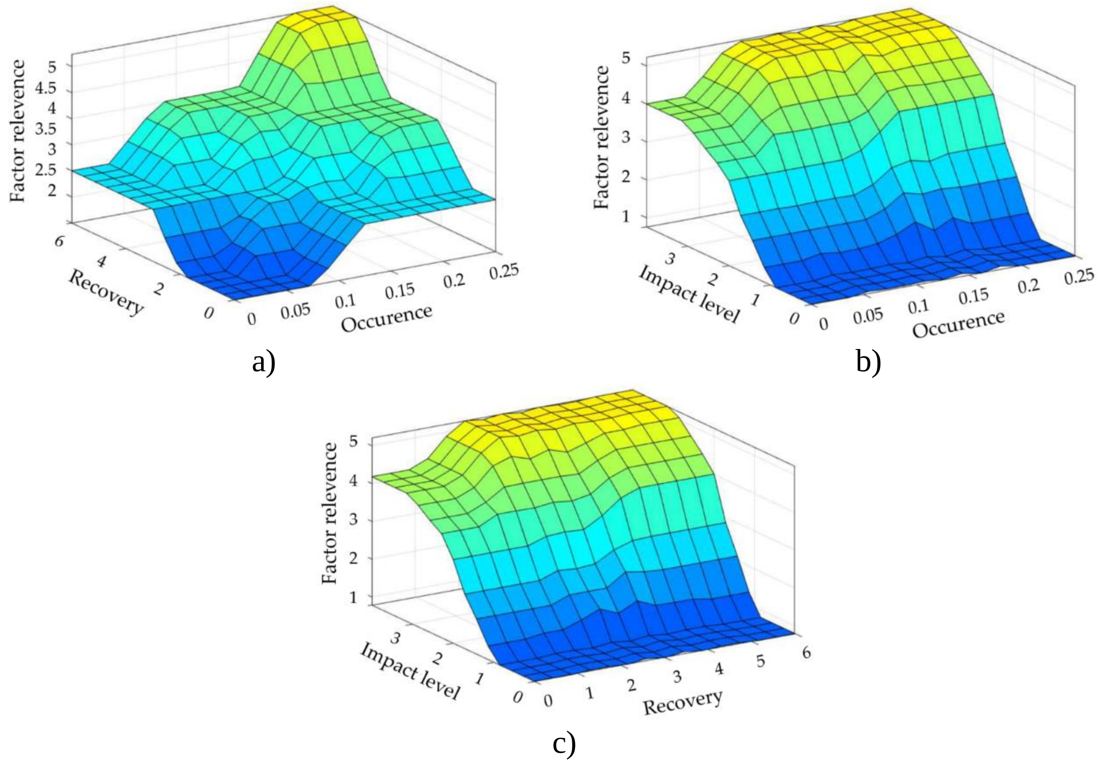


Fig. 7. The dependence of the output variable on the input variables: a) Recovery and Occurrence b) Impact level and Occurrence c) Impact level and Recovery

A three-dimensional output surface provides the entire range of the output data based on the entire range of the input data. Because of the consideration of three inputs, it was necessary to compare two of them with the obtained output. Thus, the three combinations shown in Figure 7 were analyzed. Recovery and Occurrence similarly affect Factor relevance (Figure 7a). The higher the Recovery and Occurrence, the higher the Factor relevance. The dark blue area at the bottom indicates the lowest Factor relevance, resulting from very unlikely Occurence and very short Recovery. Imbalanced influence on Factor relevance is observed when comparing Impact level with Occurrence (Figure 7b) and Impact level with Recovery (Figure 7c). In both cases, the strong influence of Impact factor on Factor relevance is noticeable. Negligible Impact level results in receiving the lowest factor relevance, the value of Occurence, or Recovery is then irrelevant.

Stage III. Factors' relevance evaluation

The final stage (III) is based on the interpretation of the results. Table 4 summarizes the results of the analysis of selected factors interfering with the sensor system of the autonomous forklift truck characterized in Subsection 2.1.

Table 4. Results of factor relevance fuzzy-based analysis

Considered environmental factor	Occurence	Recovery	Impact level	Factor relevance
condensation on the sensor surface	0.58	5.5	4	5.24
sub-zero outside temperature	0.1	0.01	0.05	0.84
fog	0.1	6	4	5.19
dust	0.01	1	1	0.768

The Occurrence criterion was considered first for the possibility of condensation on sensor surfaces. The minimum, maximum, and average temperatures in 2021 for each month were considered. For an assumed indoor temperature of 21 °C and humidity of 60%, a dew point of about 13 °C was calculated. When the temperature of the sensor housing is reduced to below 13 degrees, condensation will occur. Seven months out of twelve in 2021 (similar in 2020) had undesirable temperatures; hence, the Condensation Occurrence was determined as 0.58. Based on the testing performed in the climate chamber, Recovery was assigned a rating of 5.5. The occurrence of condensation leads to an inoperability of the sensors and thus to an inability to perform basic tasks. The impact level was assessed as 4.

Temperatures below zero in 2021 occurred for 40 days, so the Occurrence was determined as 0.1. Our tests show that sub-zero temperatures do not adversely affect the sensors. For this reason, the Recovery and Impact level were assigned 0.01 and 0.05, respectively.

Based on tests performed, publicly available fog statistics in Poland, and expert opinions, the Occurence of fog was determined as 0.1, recovery as 6, and Impact level as 4.

The ratings assigned to the dust factor are based on the characteristics of the ground present in the system under study.

Factor relevance obtained the lowest for dust and the highest for condensation indicating the necessity of considering the condensation and fog factors in the design of the sensor system of the autonomous forklift truck. The dust and sub-zero temperature factors can be ignored due to very low Factor relevance.

DISCUSSION

The proposed method allows the design of a mobile robot’s sensor system considering any operating environment. Three defined criteria form the basis for the evaluation of any factor influencing the sensor system on a five-point scale, both in terms of occurrence and severity (understood as impact level effect and recovery time). It allows the ranking of the identified factors occurring in the studied robot work system in terms of their relevance. Determination of the most relevant factors results in a reduction in the number of sensors, fulfilling the Design for Logistics assumptions. However, the method does not set a fixed boundary indicating for which value of Factor relevance the system needs to be modified. This is because the accepted Factor relevance level will vary depending on, among other things, the system designer's requirements. With people sharing the workspace with the mobile robot in the system, the acceptable level of the indicator will be much lower than in a system with no humans.

The general aim of our method is to support the mobile robot’s sensor system design in the context of Design for Logistics concept assumptions. A literature review has shown a definite lack of such methods. The effects of different environmental factors on different types of sensors are known. However, individual sensors are considered rather than the whole system. Additionally, the selected sensor is always tested in relation to the selected factor. The frequency of Occurrence of the factor is not taken into account, neither is resilience defined by us as Recovery. Our method is a novel method for evaluating environmental factors for their relevance. To the best of our knowledge from the literature review, there is a lack of such methods supporting sensor system design. Therefore, it is not possible to compare our results with the results of other methods.

Experts are able to directly design a sensory system without any support method; currently, this is how sensor system design is approached. However, our method allows us to indicate which factors can be ignored and which will significantly influence the considered variant of the sensor system design. In this way it is possible to decide whether to accept the system's current design (meeting the requirements) or to make changes due to the need for greater protection against environmental factors in the system. Experts are able to identify the environmental factors present in the system; however, determining their importance is a complex issue. Occurence, Impact level and Recovery should be taken into consideration here. Omission of these criteria and omission of factor relevance analysis may result in protection against all identified factors, leading to redundancy and additional costs.

SUMMARY AND FUTURE STEPS

Designing a sensor system for a mobile robot requires separating two groups of sensors: exteroceptive and proprioceptive. With regard to exteroceptive sensors, the problem arises in selecting the appropriate number and type of sensors, their proper placement, interpretation of data coming from different sources (sensor fusion), and further testing of the developed solution. Inherent in all of the listed groups of issues are undoubtedly environmental factors. These factors may more or less negatively affect the operation of a sensor system. In the literature, interferences of sensor operation in indoor and outdoor applications under the influence of environmental factors have already been indicated more than once. However, the focus each time is only on the effect of the selected factor on the sensor under consideration. Thus, selected sensors are evaluated with respect to selected factors. Additionally, the sensor system is not considered comprehensively, but through the prism of its individual components. In addition, the occurrence frequency of the factor and the time for the system to return to full operability after the factor is no longer present are ignored.

In view of the above, we propose a reverse approach to that used in the literature. Instead of evaluating the sensor in relation to the factor, we evaluate the identified factors with reference to the entire sensor system. We proposed a three-stage evaluation method based on fuzzy logic. The evaluation does not only consider the impact of the factor, but also the frequency of occurrence and the time for the object to return to a fully operational state. In this way, we consider the resilience and robustness of the sensor system in terms of environmental factors, which is very rarely considered in the literature despite its significance in mobile robot operation. The multiplicity and diversity of environmental factors is the biggest challenge when implementing mobile robots in a changing, uncertain environment. By evaluating the factors and thus prioritizing them using our method, only the most important factors from the designer's point of view can be taken into account. This can translate into cost reduction and shorter implementation time. In addition, the assumptions of DfL are met.

The implementation of the proposed method is presented on an example of an autonomous forklift designed for indoor operation with outdoor capability. However, the method can be used in the design of the sensory system of any mobile robot.

Our future work in the considered research field will focus on the development of the proposed method. In expert methods (such as the one proposed by us), a non-negligible key step is the selection of experts whose opinions determine the validity of the obtained results. Therefore, we plan to consider the expert selection problem.

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ORIGINAL PAPER

EFFICIENCY IMPROVEMENT OF AUTOMOTIVE ASSEMBLY LINES USING SIMPLE ASSEMBLY LINE BALANCING PROBLEM TYPE-E

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ABSTRACT. Background: An assembly line is a technique used in mass production industries, especially in the automotive industry; it consists of many workstations organized along a conveyor belt system or other material handling equipment. The assembly line balancing problem (ALBP) involves assigning assembly tasks to workstations on the line while meeting optimization goals. It is considered a critical issue in operations management because it directly affects the productivity of the entire manufacturing system.

Methods: Based on the mathematical model previously developed by (Esmaeilbeigi, Naderi, and Charkhgard 2015) for the E-type SALBP problem, we proposed a new model adaptable to the automotive sector. The proposed model uses new feasibility rules and optimizes constraints in order to propose better balancing results and efficiency.

Results: A computational experiment is presented in this article, using the newly developed model to balance an assembly line in an automotive manufacturing plant consisting of 5 workstations.

Conclusions: The experimental results show that the proposed model improved the line efficiency by 15%, which proves that the proposed method has good robustness.

Keywords: Assembly line balancing, Automotive industry, SALBP, SALBP- E, Efficiency.

INTRODUCTION

During the last decade and especially after the COVID-19 pandemic, most of the manufacturing units worldwide have shown a deep concern to improve their business standards to remain in the competitive marketplace (S. E. A. E. El Ahmadi & El Abbadi, 2023; Hussain & Jan, 2019). In addition, balancing assembly lines is one of the pillars of the current industrial revolution.

The objective of the assembly line balancing problem (ALBP) is to assign multiple tasks to a set of workstations such that the precedence relations are satisfied, and some measurements of effectiveness are optimized in order to increase the system productivity (Ahmadi & Abbadi, 2020; S. E. A. El Ahmadi & El Abbadi, 2022).

The ALB problem has frequently been the subject of interest for researchers in recent years. Propositions of solutions to the balancing problems are widely reported in the literature. (Thangavelu & Shetty, 1971) and (Deckro & Rangachari, 1990) proposed mathematical models for solving the problem. (Kilincci & Bayhan, 2006) and (Kilincci, 2010) proposed Petri-net algorithms. (Ponnambalam, Aravindan, et Mogileeswar Naidu 2000), (Lee et al., 2001), (Jiao et al., 2006), (Nearchou, 2008) and (Yeh & Kao, 2009) presented heuristics to resolve the problem, such as bidirectional heuristics. (Sabuncuoglu et al., 2000), (Kim et al., 2009) and (Wang et al., 2012) proposed genetic algorithms as a solution for the SALB problem. (Hong & Cho, 1997), (Baykasoglu, 2006) and (Roshani et al., 2012) adopted the simulated annealing algorithms as a solution to the balancing problem. (Baykasoglu & Dereli, 2008), (Lai & Liu, 2009) and (Fattahi et al., 2011) proposed the ant colony optimization algorithms as a solution.

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(Chica et al., 2010) presented a memetic algorithm as a solution for the problem based on a new local search technique used for the convergence.

(Erel & Sarin, 1998), (EL AHMADI et al., 2019), and (Saif et al., 2014) proposed review articles of the assembly line balancing problems.

There are different kinds of assembly line balancing problems., The basic classification proposed in the literature is the one proposed by (Saif et al., 2014), in which he divides the balancing problems into two major ones as seen in figure 1: simple problems (SALBP) and general problems (GALP).

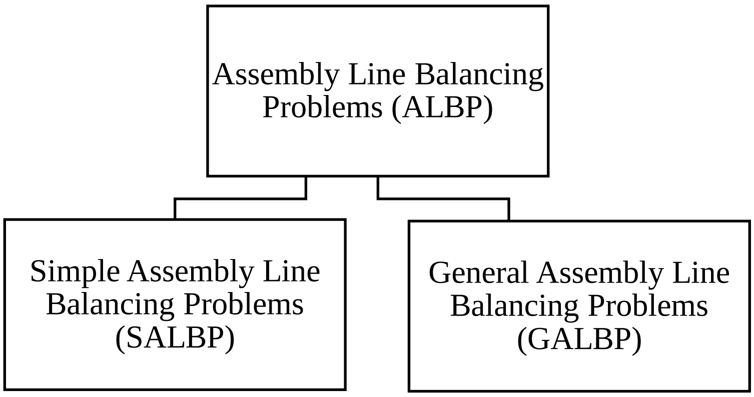

Fig. 1. Classification of Assembly Line Balancing Problems

GALBP refers to General Assembly Line Balancing Problems, which include the complex problems of balancing, namely, the mixed model line balancing problem, U-shaped assembly line problems, robotic assembly line balancing problem, and multi-objective assembly line problems.

SALBP refers to Simple Assembly Line Balancing Problems. It's the simple version of balancing problems, where the objective is to minimize the cycle time for a fixed number of workstations and vice versa. Researchers in literature proposed to divide the SALB problem into three types SALBP type 1, type 2, and type E (Jirasirilerd et al., 2020), as shown in Table 1:

Table 1. Description of SALBP problems

Problem	Variables to minimize	Variables to maximize	Fixed variables
SALBP type 1	Number of workstations	-	Line cycle time
SALBP type 2	cycle time	-	Number of workstations
SALBP type E	cycle time and Number of workstations	Line Efficiency	-

For the line balancing problems in the automotive sector, the best approach is to minimize simultaneously the cycle time and the number of workstations, in order to maximize the line efficiency (Jusop & Ab Rashid, 2015), hence, the choice of the SALBP-E problem in this paper.

The scientific goal of this article is to propose a new mathematical model that balances automotive assembly lines based on minimizing the total idle time and introducing new feasibility rules and new constraints for the cycle time and other inputs.

Materials and Methods

Presentation of the existing model

(Esmaeilbeigi et al., 2015) proposed a model based on the optimization of the upper and lower bounds of the cycle time and the number of workstations. The authors of this article have chosen this model as a basic model. This model defines the SALBP-E problem as follows: "The total amount of work required to assemble the final product is divided to a group of elementary tasks. These tasks are optimally assigned to specific workstations while minimizing the cycle time and the number of workstations at the same time while respecting the given upper and lower bounds, in order to maximize the efficiency of the line". In order to establish the basic mathematical model, the following notations and assumptions are adopted by (Esmaeilbeigi et al., 2015).

Notations:

n Number of tasks $(i = 1 \dots, n)$

m Number of stations $(j = 1 \dots, m)$

t_i Task time for task i

t_{max} The maximum of the task times t_i

t_{min} The minimum of the task times t_i

t_{tot} Summation of task times $t_{tot} = \sum t_i$

T Total time spent on the assembly line $T = t_{tot} + t_{dl}$

C Cycle time

E_f Efficiency of the assembly line

C_{max} Cycle time upper bound

C_{min} Cycle time lower bound

M_{max} Number of stations upper bound

M_{min} Number of stations lower bound

E_i Earliest workstation of task i

L_i Latest workstation of task i

P the set of precedence relations $(m, k) \in P \rightarrow taskmstartsbeforetaskk$

$$X_{ij} = \begin{cases} 1, a\ task\ i\ is\ assigned\ station\ j \\ 0, \wedge\ otherwise \end{cases}$$

$$\delta_j = \begin{cases} 1, a\ task\ is\ assigned\ station\ j \\ 0, \wedge\ otherwise \end{cases}$$

The upper and lower bounds of number of workstations M_{max} and M_{min} are predefined in order to respect the design and capacity of the factory:

M_{max} and M_{min} are given and C_{max} and C_{min} are defined by (Esmaeilbeigi et al., 2015) using the following formula:

$$C_{min} = max\left\{\lceil\frac{t_{tot}}{m}\rceil, t_{max}\right\} \quad (1)$$

$$C_{max} = max\left\{2 \times \lfloor\frac{t_{tot}}{m}\rfloor, t_{max}\right\} \quad (2)$$

In order to check the validity of data, the following condition must be respected:

$$t_{max} \leq C_{max} \leq t_{tot} \quad (3)$$

Mathematical model:

$$SALBPE: minT \quad (4)$$

Subject to: $\sum_{j=E_i}^{L_i} X_{ij} = 1$ (5)

$$\sum_{j=E_w}^{L_w} w.X_{wj} \leq \sum_{j=E_z}^{L_z} z.X_{zj} \forall (w, z) \in P \quad (6)$$

$$\delta_j \in \{0,1\} \quad (7)$$

$$X_{ij} \in \{0,1\} \quad (8)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C \quad (9)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C_{Max}.\delta_j \quad (10)$$

Constraints:

- The objective function (4) minimizes the line capacity in order to maximize the line efficiency
- Constraint (5) guarantees that a task is not assigned to more than one workstation
- Constraint (6) guarantees that the precedence relations are respected
- Constraint (7) ensures that the decision variable δ_j is binary, and it is used to indicate whether any task is assigned to station *j*
- Constraint (8) ensures that the decision variable X_{ij} is binary, and it is used to indicate whether task*i* is assigned to station *j*
- Constraints (9) and (10) impose that for any station j, the total time $\left(t_i + t_{dlj}\right)$ is lower than the line cycle time and the upper bound of the cycle time.
- The procedure is run for all possible m (number of workstations) until finding the optimal configuration and best efficiency.

Critical review of the model

The mathematical model studied in the previous section is adapted to assembly lines that do not require observance of the chronological order of the assembly operations, such as the assembly lines of textile, plastic, and other industries. On the other hand, in the automotive industry, the assembly lines must carefully respect the rules of chronological order of the execution of the tasks in order to avoid the assembly of one part before the following part in the logical assembly scheme. Moreover, the existing model does not take into account the waiting time in each workstation and assumes that the flow between workstations is a continuous flow, which is not applicable to automotive assembly lines due to the repetitive stops of the line for certain causes such as breakdowns, shortages, starvation of the lines, and other possible causes.

The existing model focuses on minimizing the total time spent on the assembly line, which requires more computational time, especially for large problems. Therefore, the authors propose a new model that takes into account precedence and feasibility constraints, and aims to maximize the efficiency of the assembly line while minimizing the number of workstations and the cycle time of the line.

FORMULATION OF THE NEW MODEL

Presentation of the proposed model:

The proposed model is based on minimizing the idle time of the line instead of the line capacity and introducing the feasibility rules and waiting time to the existing model in order to adapt it to the automotive sector. In order to establish the new mathematical model, the following notations and assumptions are adopted.

Notations:

t_{dlj} Idle time of the station j ($t_{dlj} \geq 0$

t_{dl} Idle time of the assembly line $t_{dl} = \sum t_{dlj}$

t_{wj} Waiting time of the station j ($t_{wj} \geq 0$

t_w Waiting time of the line $t_w = \sum t_{wj}$

F_{ij} Feasibility rule

$$F_{ij} = \begin{cases} 1, task\ i\ is\ feasible\ in\ station\ j \\ 0, otherwise \end{cases}$$

As seen earlier, the objective of the SALBP-E is to maximize the efficiency of the line, which can be calculated using the formula:

$$E_f = \frac{t_{tot}}{T} = \frac{t_{tot}}{t_{tot}+t_{dl}+t_w} \quad (11)$$

t_{tot} and t_w are constant values while t_{dl} is variable; therefore, we can focus on minimizing directly the idle timet_{dl} to maximize the line efficiency.

Mathematical model:

The new proposed model is formulated as follows:

$$SALBPE: min \quad (12)$$

Subject to: $\sum_{j=E_i}^{L_i} X_{ij} = 1$ (13)

$$\sum_{j=E_w}^{L_w} w.X_{wj} \leq \sum_{j=E_z}^{L_z} z.X_{zj} \forall (w,z) \in P \quad (14)$$

$$\delta_j \in \{0,1\} \quad (15)$$

$$X_{ij} \in \{0,1\} \quad (16)$$

$$F_{ij} \in \{0,1\} \quad (17)$$

$$X_{ij} = \begin{cases} 0, \wedge F_{ij} = 0 \\ 1, \wedge F_{ij} = 1 \end{cases} \quad (18)$$

$$C_{min} \leq C \leq C_{max} \quad (19)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C \quad (20)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C_{Max}.\delta_j \quad (21)$$

Constraints:

- The objective function (12) minimizes the idle time of all the stations of the assembly line, which maximizes the line efficiency as seen earlier in equation (4).
- (13) guarantees that each task is assigned to one and only one workstation.
- Constraint (14) ensures respecting the precedence relations.
- Constraint (15) ensures that the decision variable δ_j is binary, and it is used to indicates whether any task is assigned to the station j.
- Constraint (16) ensures that the decision variable X_{ij} is binary.
- Constraint (17) ensures that the feasibility variable is binary, while constraint (18) guarantees that only feasible tasks are assigned to each workstation.
- Constraint (19) imposes the lower and upper bounds of the cycle time.
- Constraints (20) and (21) imposes that for any station j, the total time $(t_i + t_{dlj})$ is lower than the line cycle time.
- The algorithm is run for all possible m (number of workstations), until finding the optimal configuration and best efficiency.

CASE STUDY

In most cases in the automotive industry, the vehicle starts from the stamping section, goes to the metallurgy section, to the painting section, and finally enters the assembly section, where our study is conducted. The assembly plant is generally composed of 2 workshops: the mechanical workshop, where the assigned workers assemble the basic mechanical parts of the vehicle, such us the engine, the radiator, and the transmission, and the interior assembly workshop, where the operators assemble all the interior pieces. Each workshop is composed of many elementary lines. Our study is conducted in the seating system assembly line, also called "ME6 line", where the operators assemble the seating system (S. E. A. El Ahmadi & El Abbadi, 2022).

Table 2 and figure 2 show the assembly sequence of the seating system in a typical car, referred to as X52. First, the parts are transferred from the centralized inventory to the buffer stocks between each two workstations, then the assembly operations of the parts are launched (seat truck, seat base, seat belt, seat cover, backrest, armrest, headrest, and central box).

Table 2. Assembly sequence of the automotive seating system

N°	Operation	Part to assemble	Part to assemble on	Time
1	Fix the seat truck on the car floor	Seat Truck	Car floor	17 s
2	Fix the seat base on the Seat truck	Seat base	Seat truck	13 s
3	Fix the backrest on the seat truck	Backrest	Seat truck	16 s
4	Fix the armrest on the central box	Armrest	Central box	16 s
5	Fix the central box on the car floor	Central box	Car floor	18 s
6	Fix the seat belt on the seat base and the central box	Seat belt	Seat base, Central box	20 s
7	Fix the headrest on the Backrest	Headrest	Backrest	15 s
8	Fix the seat cover on the seat	Seat cover	Seat	17 s

The bounds of the number of workstations are given by the process engineers of the factory due to factory design and surface restrictions, such as $M_{min} = 3$ and $M_{max} = 5$. Based on the task times shown in Table 2 and equations (1) and (2), C_{min} is computed as 33s and C_{max} is computed as 66s, which means that according to condition (12):

$$33s \leq C \leq 66s \qquad (22)$$

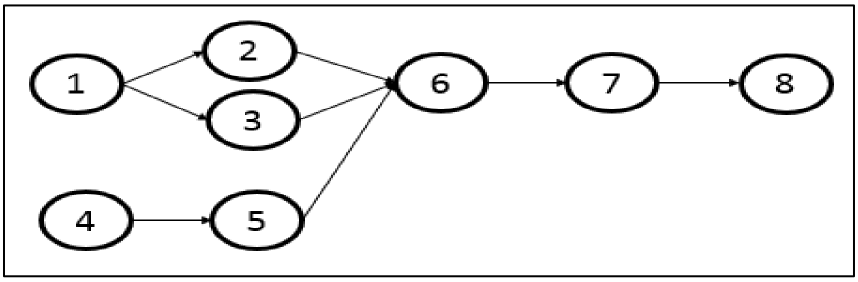

Fig. 2. Precedence graph of the studied line ME6

Based on the precedence graph (figure 2), the precedence matrix is given as:

$$\begin{pmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

RESULTS

Feasibility rules F_{ij} of each task are given by the process engineers according to technical conditions of workstations and the availability of the requirements of each task in each workstation, and these rules are formulated as shown in tables 3, 4, and 5:

Table 3. Feasibility rules for $m = 3$

Task	Feasibility Workstations
1	1, 2, 3
2	1, 3
3	2, 3
4	1, 3
5	1, 2, 3
6	1, 2, 3
7	1, 2
8	3

Table 4. Feasibility rules for $m = 4$

Task	Feasibility Workstations
1	1, 2, 3, 4
2	1, 3
3	2, 3
4	1, 3, 4
5	1, 2, 3
6	1, 2, 3
7	1, 2, 4
8	4

The algorithm is run for all possible number of workstations (3, 4, and 5), and in our case, the optimal number of workstations obtained for the studied assembly line is $m = 4$. Then the test is done for 4 workstations for all possible cycle times between the upper and lower bounds in order to find the minimum idle times as demanded in the objective function (5).

Table 5. Feasibility rules for $m = 5$

Task	Feasibility Workstations
1	1, 2, 3
2	1, 3
3	2, 3
4	1, 3, 5
5	1, 2, 3, 4
6	1, 2, 3, 4
7	1, 2, 4, 5
8	5

Based on the test done and (22), the best line efficiency obtained is $E_f = 96{,}35\%$ for an optimum cycle time $C = 34s$ with the following assignment matrix:

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The assignment of tasks to workstations is the following:

- Tasks 4 and 5 assigned to workstation 1, with a workstation time $T_{WS1} = 34s$, which is the cycle time of the line $C = 34s$ (the higher workstation time).
- Tasks 1 and 3 assigned to workstation 2, with a workstation time $T_{WS2} = 33s$.
- Tasks 2 and 6 assigned to workstation 3, with a workstation time $T_{WS3} = 33s$.
- Tasks 7 and 8 assigned to workstation 4, with a workstation time $T_{WS4} = 32s$.

Four workstations are identified by using the model, as shown in figure 3, with respect of the precedence and feasibility rules and a new cycle time of 34 seconds.

Before the implementation of the algorithm, the studied assembly line was composed of 3 workstations with a cycle time $T_c = 52s$ and the workstation times vector $T_{WS} = (46{,}34{,}52)$, which guarantees an efficiency $E_f = 84{,}615\%$.

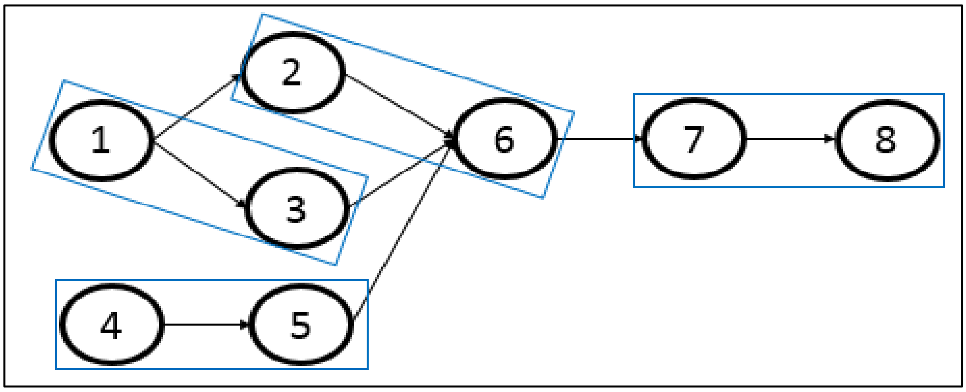

Fig. 3. Studied line ME6 after the balancing

DISCUSSION

The use of the new algorithm improved the efficiency of the line to $E_f = 97{,}059\%$ for four workstations, with workstation times vector $T_{WS} = (34{,}33{,}33{,}32)$ and a new cycle time $T_c = 34s$, which means an improvement of 14% in the total line efficiency and a reduction of 18s in the cycle time. These results are presented in Table 6:

Table 6. Comparison of the results before and after using the proposed algorithm

	Before	After
Number of workstations	3	4
Cycle Time	52 s	34 s
Total time of the line	156 s	136 s
Idle time of the line	24 s	4 s
Efficiency	84,615%	97,059%

A comparison study is made between the results obtained based on our model and the results obtained based on other existing models in the literature. (Esmaeilbeigi et al., 2015) proposed general cutting planes and precedence-oriented valid inequalities to solve the problem and included appropriate auxiliary variables to reduce the solution time. The proposed model by (Wei & Chao, 2011) minimizes the total idle time to optimize the assembly line balancing efficiency while using two variables Ei and Li. (Zacharia & Nearchou, 2013) studied the fuzzy extension of the general version of the SALBP-E problem and considered the problem of finding a feasible balance assignment of the tasks to the stations such that both the number of the stations and the fuzzy cycle time of the line is minimized.

The results obtained from the proposed mathematical models are presented in Table 7.

Table 7. Comparison of the efficiency of the proposed model with other models from the literature

Mathematical model	Efficiency
Model proposed in this article	97,059%
(Esmaeilbeigi et al., 2015)	84,615%
(Wei & Chao, 2011)	82,231%
(Zacharia & Nearchou, 2013)	80,112%

CONCLUSION

The present research work proposed a new model for solving the SALBP type E problem in the automotive industry, in which the objective is to augment the efficiency by minimizing the number of workstations and cycle time simultaneously. The model takes into account precedence and feasibility rules and the optimization of other constraints.

LIMITATIONS OF RESEARCH

The presented model is not free from some limitations. The model will be difficult to exploit in large-scale optimization problems because of the large number of constraints presented. Moreover, although the model proposed in this paper can be generalized, it requires more improvements and adaptation efforts for multi-model or mixed assembly lines in order to obtain the optimal efficiency of the line in an optimal computation time. Future work could be to develop this proposed SALBP-E model for multi model or mixed model assembly lines.

for multi model or mixed model assembly

lines.

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ORIGINAL PAPER

UNLEASHING THE ROLE OF BLOCKCHAIN TECHNOLOGY AND GOVERNMENT SUPPORT IN GREEN SUPPLY

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ABSTRACT. Background: With the advent of the technological revolution, digitalization and automation is expected to restructure the landscape of manufacturing operations. Blockchain technology (BCT) is likely to foster information sharing and transparency and facilitate collaboration on green issues in supply chain among firms. This quantitative research investigates the role of BCT in Green Supply Chain Management (GSCM) practices and its' effect on various performances, including economic and social performance.

Method: The data was gathered from 223 firms by utilizing a survey questionnaire, and PLS-SEM was employed to analyze the hypotheses.

Results: The findings showed that BCT has a key role in the implementation of GSCM practices (comprising green purchasing and green manufacturing). The outcomes also elucidated that green manufacturing is positively associated with economic and social performance. Whereas, green purchasing is negatively correlated with economic performance and has an insignificant effect on social performance. Moreover, government support (GS) moderates the link between BCT and GSCM practices (including green purchasing and green manufacturing).

Conclusion: This research provided ample understanding about the role of BCT in implementing GSCM practices. The findings suggested that government bodies need to provide interest free loans and tax exemption to effectively implement GSCM practices.

Keywords: Blockchain technology; Green supply chain management; Logistics Management; PLS-SEM; Transportation

INTRODUCTION

In the current era of industrialization, sustainability concerns are arising across the globe. The rapid increase in industrialization and globalization have provided societies with a huge amount of benefits in terms of economic gain and enhanced production of goods and materials but has given rise to sustainability concerns. Keeping in view the enhanced sustainability problem, countries across the globe have forced countries and enterprises to take steps in order to keep balance between industrial activities and sustainability. In this regard, the research on Green Supply Chain Management (GSCM) [Sheng et al. 2023], Green intellectual capital [Asiaei et al. 2023], GHRM [Bahuguna, Srivastava & Tiwari, 2023], Green marketing [Mukonza & Swarts, 2020], Green finance [Zhou et al. 2020], and sustainability is getting attention among scholars to provide enriching details for enterprises and countries to adopt such strategies that can help manage ecological problems, as well as provide people with a healthy life. Nevertheless, the obstacles are enhancing and cropping up, which leads to suggestions for different feasible techniques for solving ecological problems, thus changing the landscape towards green operations and practices such as GSCM, which includes involvement of green criteria in all supply chain (SC) processes from production to disposal of products or goods [Umar et al. 2022]. GSCM is stated as a crucial business strategy that has the potential to eradicate the harmful effect of traditional SC

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activities and can improve the social and economic performance (ECP) of firms [Habib, Bao & Ilmudeen, 2020].

Moreover, the advent of I4.0 technologies in the current era has revolutionized the processes of GSCM [Mubarik et al. 2021; Kouhizadeh & Sarkis, 2018] and made manufacturing operations more efficient and sustainable [Khanfar et al. 2021]. Researchers have defined I4.0 as an attempt to transform and build smart systems through the integration of various technologies such as Artificial intelligence (AI), BCT, Big data analytics (BDA), Internet of things (IoT), and Additive Manufacturing (AM) [Ghadge et al. 2022]. The adoption of which can enhance the efficiency of production operations [Khan et al. 2022; Khan et al. 2023a; Khan et al. 2023b], provide transparency and visibility in SC processes, and help gain sustainable goals [Umar et al. 2021a]. Also, I4.0 is pushing automation and digitization to an unprecedented level and making possible human-machine interaction in the form of advanced robotics [Khan et al. 2021; Baur and Wee, 2015; Khan et al. 2022a; Khan et al. 2023c]. Moreover, I4.0 is unlocking the potential of sustainable firms and helps in moving towards sustainable societies and sustainable manufacturing [Sharma et al. 2020; Parmentola et al. 2022]. Of the I4.0 technologies, i.e., BCT, which is known as distributed ledger technology, have provided implication for SC sustainability. Scholars have stated that the implementation of BCT facilitates modern ways of production, provides data transparency, immutability, and smart contract facility to firms [Kouhizadeh & Sarkis, 2018], and can stimulus the adoption of GSCM practices [Ghadge et al. 2022; Khan et al. 2022b] in manufacturing firms. Similarly, Feng et al. [2022] also demonstrated that manufacturing firms can benefit from the applications of BCT in terms of higher cooperation and communication across all SC processes, improved trust and reliability, better management and information traceability, and enhanced efficiency of GSCM practices, including green purchasing and investment recovery. Moreover, scholars have indicated that GSCM consists of complex activities and adopting BCT in GSCM can effectively manage and enhance its performance [Mubarik et al. 2021]. Limited studies have been held on BCT and GSCM, and these concepts still need to be explored further [Ghadge et al. 2022]. Researchers have also suggested conducting research on examining the role of BCT in GSCM practices [Yu, Khan & Umar 2022; Khan et al. 2023d]. Thus the present study seeks to fill the existing gap in literature by investigating the effect of BCT on GSCM practices and their role in achieving social and financial performance. Moreover, the current study also analyzes the moderating role of government support among BCT and GSCM practices.

The paper is organized as follows: section 2 indicates the theoretical underpinning and research proposition, while methodology is presented in section 3, followed by results in section 4, and discussion in light of previous research is indicated in section 5. Section 6 illustrates the conclusion and policy implications, and future research plans are in the last section.

Theoretical Underpinning and Research Proposition

The resource-based view (RBV) is the influential theory that is used to explain specific unique resources of firms that yield sustained competitive advantage [Barney et al. 2011]. RBV helps firms to examine their capabilities and resources and empower them to perform better and create a sustainable competitive advantage. Firm resources include information, assets, attributes, capabilities, and organizational processes, which can be controlled by firms, and help firms implement such strategies that improve their effectiveness and efficiency. The resources are categorized into tangible (e.g., information technology (IT) infrastructure) and intangible (e.g., knowledge or process knowledge) [Barratt and Oke, 2007]. Moreover, resources must be inimitable, rare, and non-substitutable to attain a competitive edge [Barney, 1991] and higher performance [Malik et al. 2020]. In contrast, capabilities pertain to the firm's approach in utilizing resources with organizational processes to achieve the desired outcome [Liu et al. 2016].

In this study, I4.0 technology such as BCT is considered the most valuable resource of a firm

[Bressanelli et al. 2018]. It has the ability to provide transparency, automation, and integration among inter and intra-organizational processes [Wang et al. 2020] and ultimately enhance the productivity of SC processes. Bag et al. [2021] also elucidated that along with I4.0, various other resources, i.e., GHRM, green logistics, and ecological knowledge can aid organizations in enhancing ECP and social performance (SP) [Umar et al. 2022a]. It is generally stated that technological resources have a significant impact on the adoption of GSCM practices. Particularly, the adoption of I4.0 enhances the capability of firm in performing numerous processes, such as traceability of products, inventory management, development of green production lines, self-configuration of workstations, and remanufacturing, hence ameliorating the whole manufacturing system [Mohamed & Al-Jaroodi, 2019; Nandi et al. 2021]. Therefore, investigating how the adoption of BCT helped in the implementation of various sustainable practices is vital to form a viable strategy and improve sustainable performance.

BCT and GSCM practices

Industry 4.0 (I4.0) is a new paradigm of autonomous and smart manufacturing and known as the fourth industrial revolution, in which modern technologies are integrated with manufacturing systems with the aim of attaining sustainable performance [Bai et al. 2020]. In today's technological era, 14.0 technologies are adopted by firms to develop green production lines and improve SC performance [Fatorachian & Kazemi, 2021]. I4.0 includes BCT, IoT, AI, cybersecurity, BDA, and robotics [Jamwal et al. 2021, Massaro et al. 2021]. Its implementation is transforming business models and enabling firms to move toward sustainable operations [Li et al. 2017]. Previous literature has illustrated the importance of I4.0 technologies in adopting GSCM practices to mitigate the adverse environmental externalities [Khan et al. 2023a]. For instance, Mastos et al. [2020] indicated that implementing IoT enabled firms to facilitate GSCM practices by reducing pollutants and enhancing resource availability and response time optimization. Kouhizadeh and Sarkis [2018] also demonstrated that the implementation of BCT aids enterprises to maintain the information regarding supplier and material, as well as origin, quality, and quantity of products, which helps enterprises to ensure green purchasing. In addition, scholars have also stated that through BCT, lifecycle assessment of any product can be carried out by utilizing the actual data of a product instead of an estimated value, which is the contribution of this revolutionary technology.

Recently, researchers have stated that BCT is an innovative technology that promotes GSCM practices through its various applications and helps in optimizing and managing ecological issues such as minimizing carbon emission and waste from production and transportation [Elhidaoui et al. 2022]. Similarly, Böckel, Nuzum & Weissbrod [2021] indicated that BCT has a crucial role in the execution of green manufacturing (GM) and green purchasing (GP), as its features improve transparency and traceability and provide immutability and security in green operations. Moreover, Khanfar et al. [2021] affirmed that the adoption of BCT in green/sustainable manufacturing had improved the prediction accuracy by providing quality data for prediction analysis. Also, it has minimized production time through sharing real-time information and enhanced the flexibility of manufacturers through innovative process development, which helped in responding to changing market demand and meeting customer requirements. However, the literature still lacks empirical research on the link between BCT and GSCM practices. Thus, the current research has been carried out to examine the role of BCT in crucial GSCM practices such as GP and GM. Hence, this research hypothesized that:

- H1a: BCT has a positive and significant effect on GP.
- H1b: BCT has a positive and significant effect on GM.

GSCM Practices and Performance

GSCM is a proactive approach in which ecological thinking is implemented among all phases of SC, from purchasing to final product and from finished product to recycling [Srivastava, 2007]. GSCM encompasses various practices such as GP, GM, green design, and green logistics. The adoption of these practices has a crucial role in enhancing TBL, i.e., ecological, financial, and social performance. The traditional way of manufacturing is causing various ecological issues [Tseng et al. 2021]. Thus, the adoption of sustainable practices has the potential to mitigate ecological adversities [Ozceylan et al. 2014]. The literature also tends to support the position that green practices can help minimize waste and harmful emissions, thus helping in conserving the natural environment and human health [Khan & Yu, 2021]. Among GSCM practices, GM is sought as the most crucial practice, as it helps in enhancing manufacturing capability and productivity through effectively utilizing resources, which improves firm performance [Baah et al. 2021; Habib et al. 2021]. Past research also confirmed that effective consumption of product/material, energy, and green manufacturing operations are the crucial drivers that help in improving sustainability performance [Afum et al. 2020; Cankaya & Sezen, 2018]. GM also ensures efficient consumption of resources and improves firms' operational performance through enhancing functionality of materials and products [Abdallah & Al-Ghwayeen, 2019; Leong et al. 2019]. Existing studies also elaborated that sustainable manufacturing practice is focused on minimizing natural resource consumption and ecological adversities such as toxic and hazardous chemicals and carbon emissions, which helps to improve SP and ECP [Abdul-Rashid et al. 2017]. In addition, GP, which is focused on acquisition of green product/material and evolving strong relationships with suppliers [Zhu et al. 2008], also helps to enhance ECP and SP. Moreover, the literature has provided mixed findings about the impact of GSCM practices on various performances. For instance, Khan et al. [2017] carried out a study on Chinese production enterprises to assess the role of GP in ECP; the scholars have affirmed a negative link between GP and ECP. Contrastingly, Çankaya & Sezen [2019] and Amjad et al. [2022] tend to support that GP is positively linked with ECP. Younis et al. [2020] studied the association among GSCM practices and firm performance and affirmed that GP has an insignificant effect on SP. This indicates that green practices have a varied impact on organizational performance and needs to be examined more comprehensively. Therefore, GP and GM are examined in the current study. On the bases of the above-mentioned arguments, this research hypothesized that:

- H2a: GP has a positive and significant effect on ECP.
- H2b: GM has a positive and significant effect on ECP.
- H3a: GP has a positive and significant effect on SP.
- H3b: GM has a positive and significant effect on SP.

Government support as Moderator

The notion of GSCM is still underexplored in manufacturing enterprises of emerging economies [Malik et al. 2020]. Most of the firms in these regions are just using the logo of green practices. Scholars have also affirmed that there is less focus on implementation of GSCM practices in manufacturing enterprises of emerging economies [Khan & Yu, 2021]. The reason behind this is an inadequate provision of government support (GS) and resources [Martín-Gómez et al. 2019]. GS in this research is defined as the support given by the authorities to strengthen the execution of GSCM practices and advanced technologies such as BCT [Hussain et al. 2022]. Undoubtedly, governmental institutions have a major role in the completion and implementation of any projects. In emerging economies, the government is the financier, while the other authorities are responsible for the maintenance of the projects. Prior literature has indicated that government support is a key driver of advanced technologies [Bosman et al. 2019; Majumdar et al. 2021] and GSCM practices [Ilyas, Hu & Wiwattanakornwong 2020]. The legislative rules and policies of governmental authorities can push industries to move towards I4.0 technologies to enhance the adoption of GSCM practices.

Sustainable development goals have also forced governmental bodies to support communities in conserving natural resources [Ilyas, Hu & Wiwattanakornwong 2020]. Thus, firms are also affected by pressures from governmental institutions to achieve sustainable initiatives [Schoenherr et al. 2014]. In emerging economies, the government can promote the adoption of green/sustainable practices [Luthra et al. 2015] and advanced technologies. Various departments have been created to support the execution of advanced technologies and green practices. Thus, on the basis of the above arguments, it can be stated that GS can assist in the adoption of BCT and green practices. Hence, the current study hypothesizes that:

- H4a: GS significantly moderates the relationship between BCT and GP.
- H4b: GS significantly moderates the relationship between BCT and GM.

Research Methodology

The primary objective of embracing GSCM practices in SC is to improve the social and financial outcomes by minimizing waste, harmful emissions, cost of energy consumption, and enhancing safety for employees. GSCM practices enabled businesses to enhance their organizational performance. The researcher indicated that GP, ecological product design, and GM were widely discussed green practices [Naim et al. 2022; Khan, Yu, & Umar 2022; Khanra et al. 2022; Hassan & Jaaron, 2021; Jabbour et al. 2017].

In the current research, BCT was linked with GSCM practices to improve social and financial performance. The data were collected from large manufacturing firms which are registered on the Pakistan Stock Exchange. Manufacturing firms were chosen because these firms are jeopardizing the sustainability of the country. Table 1 indicates the demographic profile of the respondents. The data were collected in two phases; the 1st phase lasted from November 2021 to January 2022, and 163 questionnaires were returned. Those large manufacturing firms who did not respond in the first phases were reminded through a telephone call. Whereas, in the second round during February and March of 2022, only 79 questionnaires were returned. Out of the total number, 19 questionnaires were excluded as they were not properly filled. Thus, a total of 223 responses were utilized for analyses, which provided a response rate of 58.6%. Figure 1 indicates the theoretical framework.

The current study employed PLS-SEM for the following reasons: firstly, it can handle complex models and has a variance-based approach, which is more appropriate than a co-variance based approach. Secondly, it can handle both formative and reflexive models. Thirdly, it can provide optimal prediction accuracy. Lastly, it provides reliable results in the case of a small sample size.

Fig. 1. Theoretical framework

Table 1. Demographic Profile of Responding Companies

	Demographic	**Variable Frequency**	**Percentage (%)**
Type of industry	Paper & board	8	3.58
	Automobile	17	7.62
	Synthetic & rayon	7	3.14
	Leather and tanneries	5	2.24
	Chemical	23	10.31
	Steel/iron	13	5.83
	Fertilizers	3	1.35
	Pharmaceutical	11	4.93
	Cable & Electrical goods	7	3.14
	Food and personal care	22	9.87
	Glass & ceramic	8	3.59
	Sugar and allied	26	11.66
	Textile	73	32.74
Number of employees in company	250 – 500	67	30.0
	501—1000	93	41.7
	1001-2000	41	18.4
	More than 2000	22	9.9
Position	Senior level management	74	33.2
	Middle level management	149	66.8
Job experience in Supply chain	Less than 1 year	6	2.6
	1 – 5 years	58	26.0
	6 – 10 years	74	33.2
	11 – 15 years	42	19.0
	16 – 20 years	34	15.2
	More than 20 years	9	4.0

Note: Senior management = SC director, SC manager, Purchase manager, Production manager, Inventory manager Middle level: SC senior officer, warehouse officer, purchase officer, transport officer.

RESULTS AND DISCUSSION

Measurement model

The current research evaluated convergent and discriminant validity for the measurement model. Table 2 illustrates the values of construct validity and reliability, in which all the values of composite reliability (CR) are greater than the threshold value of 0.7 [Hair et al. 2011], and the values of average variance extracted (AVE) also meet the criteria value of 0.5 [Hair et al. 2017]. As the value of AVE is higher than the cutoff value, this indicates that the constructs have well established convergent validity.

Discriminant validity is the second type used for validity evaluation. HTMT ratio of correlation is used to evaluate the discriminant validity. The value of HTMT must be less than 0.9 [Henseler et al. 2015]. The values in table 3 meet the thresholds criterion, which indicates that discriminant validity has been established.

Table 2 Construct Validity and Reliability

Variables	**Composite Reliability**	**Average Variance Extracted**
BCT	0.896	0.635
GP	0.824	0.540
GM	0.809	0.520
ECP	0.880	0.650
SP	0.864	0.624
GS	0.849	0.653

Note: BCT = Blockchain technology, GP = Green purchasing, GM = Green manufacturing, ECP = Economic performance, SP = Social performance, GS = Government support

	GM	GP	BCT	GS	ECP	SP
GM						
GP	0.287					
BCT	0.387	0.844				
GS	0.251	0.753	0.575			
ECP	0.866	0.132	0.241	0.158		
SP	0.762	0.180	0.228	0.161	0.785	

Table 3 Heterotrait-Monotrait Ratio (HTMT)

Table 4. Summary of hypotheses

Hypotheses	Effect	Original Sample	T Statistics	P Values
H1a	BCT -> GP	0.512	7.823	0.000
H1b	BCT -> GM	0.308	3.356	0.000
H2a	GP -> ECP	-0.083	1.689	0.046
H2b	GM-> ECP	0.697	19.165	0.000
H3a	GP -> SP	-0.036	0.661	0.254
H3b	GM-> SP	0.598	13.875	0.000
H4a	GS*BCT -> GP	0.152	3.137	0.001
H4b	GS*BCT -> GM	0.144	2.432	0.008

Table 5. Collinearity assessment

	GM	GP	BCT	GS	ECP	SP
GM					1.039	1.039
GP					1.039	1.039
BCT	1.275	1.275				
GS	1.275	1.275				
ECP						
SP						

Structural Model

The structural model indicates the associations among the constructs that were hypothesized in the research model [Hair et al. 2014]. After the establishment of the outer model, the proposed hypotheses were observed. The summary of hypotheses is illustrated in Table 4.

The findings illustrate that BCT has a significant effect on GP ($\beta = 0.512$, $p < 0.01$) and GM ($\beta = 0.308$, $p < 0.01$). The outcomes also indicated that GM has a key role in improving ECP ($\beta = 0.697$, $p < 0.01$) and SP ($\beta = 0.598$, $p < 0.01$). However, GP is negatively linked with ECP ($\beta = -0.083$, $p < 0.05$) and has an insignificant effect on SP ($\beta = -0.036$, $p = 0.245$). Moreover, the findings elucidated that GS substantially moderates the link between BCT and GP ($\beta = 0.152$, $p < 0.01$) and GM ($\beta = 0.144$, $p < 0.01$).

Table 5 indicates the values of VIF, which are less than 5, representing no issue of collinearity in our estimated model. R^2 evaluates variance elucidated in each of the endogenous constructs [Hair et al. 2022]. The R^2 value ranges from 0.02 – 0.12 is considered small, 0.13 – 0.25 is moderate and 0.26 and above is substantial. The values of R^2 are indicated in table 6.

BCT explained 54.6% of the variance in GP ($R^2 = 0.546$) and 10.2% of the variance in GM ($R^2 = 0.102$), respectively. As the value of R^2 for GP is above 0.26, it is considered substantial. The value of R^2 for GM is considered small, as its value is in the range of 0.02 – 0.12. Moreover, GSCM practices (i-e., GP and GM) explained 47.1% of the variance in ECP ($R^2 = 0.471$) and 35.2% of the variance in SP ($R^2 = 0.352$). The R^2 values are above 0.26; thus, it is considered substantial.

Predictive relevance is measured through Stone-Geisser's Q^2 [Geisser, 1974]. The values of Q^2 in Table 6 indicate that all the exogenous constructs considered in the current study have predictive relevance.

Table 6. Predictive relevance

Variables	Q Square	R Square
GM	0.046	0.102
GP	0.274	0.546
ECP	0.300	0.471
SP	0.215	0.352

Discussion

The result of H1a in Table 4 indicated that BCT has a positive impact on GP. This outcome is aligned with the findings of Bag et al. [2020]. The researchers indicated that GSCM consists of complex activities, and that the adoption of BCT in GSCM can effectively manage and enhance its performance. Kouhizadeh and Sarkis [2018] also elucidated that BCT helps in ensuring GP by managing and maintaining supplier and material information. Moreover, Ivanov et al. [2019] stated that BCT based SC allows a transparent and secure flow of information in the value chain and enhances productivity through increasing integration among enterprises.

Next, the result of H1b showed that BCT has a significant impact on GM. The current outcome is similar to the research findings of Mubarik et al. [2021], in which the authors found a positive effect of BCT on GSCM practices. The authors have also elucidated that the implementation of BCT boosts robustness in the SC process, enables firms to manage production through real-time monitoring, and keeps suppliers, customers, organizations, and other stakeholders connected in a real-time environment. Researchers have also stated that BCT is an innovative technology that improves GSCM practices through its various applications that help in optimizing and managing ecological issues, such as minimizing carbon emission from production and transportation [Elhidaoui et al. 2022; Queiroz & Wamba, 2019].

Moreover, the result of H2a indicated that GP has a negative effect on ECP ($\beta = -0.083$, $p < 0.05$). A similar finding is illustrated by Khan et al. [2018a] in their study, in which the researchers studied the production enterprises and affirmed that GP is negatively linked with ECP. The researchers have also indicated that in developed countries, ecological regulations are strict for sourcing green components from local or international suppliers and are encouraged through giving tax exemptions and low import duty to firms as compared to developing countries. The researchers are also of the view that GP enhances the cost of the overall SC system. Khan et al. [2019] also stated the similar finding that GP is negatively related with profit of enterprise because of heavy taxation and import duties on green materials and components.

Next, the results of H2b revealed that GM is significantly related to ECP ($\beta = 0.697$, $p < 0.01$). This research finding is similar to the study of Afum et al. [2020], in which the scholars analyzed the impact of GM on ECP in manufacturing firms of Ghana and stated a substantial link among GM and ECP. The researchers have also elaborated that managers need to unveil the implementation of GM to stakeholders and customers, as doing so can help firms earn more reputation. Singh et al. [2022a] also held a study to verify the influence of GM on enterprise performance, in which the scholars elaborated that the alarming increase in ecological pollution has forced firms to move towards GM. The researchers have also explained that the market position and share of enterprises can be increased if firms adopt GM. Researchers have also illustrated that the adoption of GM helps enterprises meet the requirement of stakeholders [Draghici & Ivascu, 2022] and boost their ECP [Prasad et al. 2022].

Moreover, the result of H3a illustrated an insignificant relationship among GP and SP ($\beta = -0.036$, $p = 0.245$). Similar findings are indicated by Çankaya & Sezen [2019], in which the researchers presented an insignificant effect of GP on SP. Scholars have also demonstrated that this practice has a direct influence on suppliers while having indirect influence on businesses by gaining green inputs. Moreover, Younis et al. [2020] studied the association among GSCM practices and firm performance and affirmed that GP has an insignificant effect on SP.

Next, the result of H3b indicated a substantial influence of GM on SP ($\beta = 0.598$, $p < 0.01$). Similar findings are illustrated by Abdul-Rashid et al. [2017], in which the scholars studied the impact of GM on the triple bottom line of performance. The scholars have affirmed GM as a crucial factor that can help in improving sustainable performance; moreover, the researchers have elaborated GM as an ecological initiative that can help firms in preserving the ecosystem and improve the standard of social life. Afum et al. [2020] also examined the association among GM and sustainability performance in Ghana and found substantial influence of GM on SP. The authors also discussed that Ghanaian manufacturing enterprises initiated giving green training to their workers to effectively carry out operations and to lessen the adversarial effect of production operations on the ecological system and quality of life. Similarly, Singh et al. [2022b] also carried out a study to investigate the role of GM in the production enterprises of India and affirmed that GM has a crucial role in achieving EP and SP. Scholars have also recommended adopting GM to develop sustainable products. The researchers are also of the view that GM can help firms in preserving the environment and reducing costs.

Moreover, the result of H4a and H4b indicated that GS substantially moderates the link between BCT and GP ($\beta = 0.152$, $p < 0.01$) and GM ($\beta = 0.144$, $p < 0.01$). This outcome is aligned with the research conducted by Ilyas, Hu & Wiwattanakornwong [2020], their findings also elaborated that government support facilitates GSCM practices in SMEs. The scholars are also of the view that there should be a strong link among government bodies in order to access valuable resources, as in emerging economies, most of the valuable assets that are vital for green activities are owned by the government. The result also implies that governmental bodies need to provide ease in laws for industrial firms in order to encourage green practices in SC operations and provide tax exemption and interest free loans.

CONCLUSION AND POLICY RELEVANCE

The increasing concern regarding ecological issues has forced firms to move towards sustainable operations. In the current dynamic environment, the success of enterprises is to enhance their efficiency and competitiveness by going green in SC. To provide more in-depth detail, this study investigated the role of BCT in GSCM practices including (GP and GM), and how it leads towards social and financial performance. Also, the moderation role of government support was analyzed in relationships among BCT and GSCM practices. A questionnaire was used for the collection of data from large manufacturing enterprises. The hypothesis was tested by employing PLS-SEM. The measurement model has well-established convergent and discriminant validity, and the values of variance inflation factor meet the threshold criteria, indicating no issue of common method bias.

The outcomes indicated that BCT has a significant role in the adoption of GSCM practices, including GP and GM. The outcomes also elucidated that GM is positively associated with ECP and SP. Whereas, GP is negatively related with ECP and has an insignificant effect on SP. Moreover, GS substantially moderates the link between BCT and GSCM practices including GP and GM.

The implications of the study are as follows: first, the current study enhances the literature on GSCM theoretically and prolongs the scope of SC research by analyzing the moderating role of government support among BCT and GSCM practices, which aligns the recent call in SC literature [Ghadge et al. 2022]. Second, although studies have been published on BCT, especially in developed countries, the discourse and investigation on BCT and GSCM in a Pakistani context is still less explored. This current research offers empirical observations that could be relevant for developing nations. Hence, it fills the gap by providing in-depth detail on a localized perspective of the subject matter.

For industry practitioners, the current study findings provide the direction and understanding that BCT has a vital role in effective implementation of GSCM practices. This implies that the managers can improve the adoption of GSCM practices in their enterprises through deploying BCT, which has the potential to facilitate green practices by providing security, ensuring traceability, and enhancing transparency in operations.

The findings also provide companies with the direction that GSCM practices have the potential to improve sustainable performance. This finding suggests that managers of production enterprises can implement GSCM practices in their operations. The implementation of green practices enables firms to reduce adverse pollutants, waste, and carbon emissions, thereby conserving the natural environment. Additionally, it helps companies meet the demands of stakeholders and enhances their reputation in the eyes of customers by producing eco-friendly products.

Moreover, the findings suggest that policymakers should exert pressure on production firms and develop strict rules for the implementation of green practices; doing this can help in achieving sustainability in businesses. The governmental bodies also need to develop a strong mechanism for rewards and punishment. If firms carried out unhealthy and adverse activities in manufacturing, suitable action should be taken against them, such as heavy fines and penalties to restore environmental loss and cancellation of license. Regulatory bodies can also give tax exemptions and interest free loans to those industries that implement green practices in order to pursue technological infrastructure and green practices effectively.

FUTURE RESEARCH PLAN

Like other studies, this study also has some limitations. First, this study only focused on one I4.0 technology, which is BCT, in manufacturing firms of Pakistan; future studies can be held by focusing on other I4.0 technologies such as AI and BDA in both manufacturing and service firms to provide more exhaustive explanations. Second, this research has only studied the current state of large manufacturing firms and did not examine the short or long run impact of GSCM on sustainability. Future studies can be held by using a longitudinal approach, as it will provide more exhaustive detail about the development of GSCM practices. Third, future studies can also test the same model in different countries and institutional settings or can hold comparative studies across various cultures and countries to provide more comprehensive explanations. Last, future studies can examine the role of BCT in green design and green logistics to add the body of knowledge.

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ORIGINAL PAPER

IMPACT OF INFORMATION TECHNOLOGY RESOURCES ON ENVIRONMENTAL PERFORMANCE: MEDIATING ROLE OF INTERNAL GREEN SUPPLY CHAIN INTEGRATION

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Abstract. Background: Information technology (IT) resources can play an important role in helping firms overcome the environmental issues they face by facilitating green supply chain management. This study examines the relationship between IT resources, specifically IT infrastructure resources, IT human resources and IT relationship resources, and the environmental performance of textile firms. Further, the study examines the mediating role of green supply chain integration on this relationship.

Methods: The study collected data from 512 executives working in the textile sector in the Punjab province of Pakistan, where green supply chain integration is being practiced. Smart PLS has been used for estimation results.

Results: The results of the study show that IT resources in the form of IT infrastructure resources, IT human resources and IT relationship resources have a significant association with the environmental performance of firms. Likewise, structural equation modeling (SEM) confirms that green supply chain integration mediates this relationship. **Conclusions:** The results of the study demonstrate that the improvement of IT resources can help companies achieve their environmental performance targets. Likewise, the results also suggest that companies should work on achieving green supply chain integration as it can improve their environmental performance.

Keywords: IT resources, Internal Green Integration, Environmental Performance, Pakistan, PLS-SEM

INTRODUCTION

Owing to increased pressure from regulators and the masses, organizations now clamor for practices that enhance their environmental performance and help them maintain their environment friendly status (Hashmi & Akram, 2022). Over the years, environmental performance has become an integral part of a firm's overall performance and supply chain practices have been found to have an impact on the environmental performance of firms.

In the modern age, information technology (IT) has become a critical success factor for almost every industry. With growing competitiveness, businesses are trying to get hold of IT specialists to improve their supply chain management (SCM) and use it to gain a competitive advantage (Jing, 2021). Research suggests that IT systems can improve coordination of the roles and responsibilities of supply chain participants (Ersoy et al., 2022; Nozari et al., 2021).

Evidence suggests that the sustainability of the supply chain industry is dependent on green supply chain practices. Additionally, these practices contribute to economic performance and competitiveness in a number of ways: by enhancing cost effectiveness, decreasing waste, and satisfying customer demand for eco-friendly products (Raut et al., 2021). However, if not effectively managed, the driving forces

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promoting the adoption of green supply chain (GSC) techniques can also obstruct the green transition (Jiang et al., 2022). At various stages of the process, green supply chain management (GSCM) is supported by a variety of software programs and cutting-edge technologies. These might include innovative manufacturing technologies that utilize less energy to produce products or lower the amount of hazardous materials used in the production process, and warehouse management systems (WMS) that increase warehouse efficiency (Tehrani & Gupta, 2021).

Thus, this study examines the relationship between IT resources—specifically IT infrastructure resources, IT human resources and IT relationship resources (IT-RR)—on environmental performance, as well as the mediating role of green supply chain integration. Many textile firms harness such technological capabilities to add value to their operations. Evidence suggests that information technology has revolutionized the textile sector supply chain in various ways, from improving textile production performance to stricter process control (Yuan et al., 2021). Thus, it is important to look at the role of information technology on the environmental performance of textile firms via green supply chain practices.

LITERATURE REVIEW

Information Technology Resources and Environmental Performance

The study defines IT infrastructure as shared IT resources made up of a technological physical base consisting of hardware, software, communications technologies, data, and core software applications, and a human component made up of skills, expertise, and knowledge (Pattnaik et al., 2022). These elements work together to produce IT services that are typically exclusive to an organization, or at the very least stand out from the alternatives.

Furthermore, by extending the resource-based view (RBV) to the context of green management, it is possible to define IT resources as the extent to which managerial and technical IT applications are employed to address environmental issues by encouraging green thinking both within and outside of organizational borders (Li, 2022). Previous studies have stated that IT resources include IT infrastructure, IT personnel, and IT relationship components, all of which allow the business to more successfully adopt and implement its IT-enabled initiatives (Lin, 2022). Because they assist businesses in concurrently developing and implementing a variety of green management practices, IT resources are a key driver of IT-enabled green innovations. An adaptable IT infrastructure, for instance, may help a company better track the costs, waste, and emissions associated with each stage of the supply chain (SC) and encourage employee participation in environmental efforts (Kurniawan, 2023).

The business may exchange and communicate any kind of information thanks to compatible IT infrastructure, which makes it simple to incorporate the efficient flow of information into IT applications. A high degree of flexibility makes it simple for the company to reconfigure IT applications and integrate them into supply chain planning systems. The company may also use this flexibility to adapt its IT applications in order to comply with environmental protection laws (e.g., in e-GSCM). As a result, it is expected that IT infrastructure resources will be needed to enable internal integration and external collaboration involving e-GSCM. It is possible that a more flexible IT architecture that makes it easier to keep track of expenses, waste, and emissions at various levels of the SC may encourage greater employee engagement in environmental programs (Li et al., 2020). IT experts who are knowledgeable in the field may advocate for the use of environmentally friendly technology and solutions that are efficient in terms of energy consumption. In addition, they will be able to successfully combine IT strategy with environmental objectives. It is envisaged that a sizable IT team will be able to facilitate communication, coordination, and transparency between a firm and its SC partners in order to build external trust in the company's commitment to environmentally responsible practices (Shah & Soomro, 2021).

Also, because e-GSCM demands tight cooperation and information sharing within and between enterprises enabled by IT applications, IT resources are essential. In order to deploy e-GSCM, businesses need to maintain a portfolio of IT resources (such as IT infrastructure, staff knowledge, and IT-RR; Lo et al., 2018). Therefore, three categories of IT resources (including IT infrastructure, IT human resources, and IT-RR) may be taken into account as possible predictors of e-GSCM deployment from the standpoint of RBV. Additionally, prior research has failed to offer empirical support for a particular class of IT resources and instead concentrated mostly on the impact of general information services support (e.g., IT investments, internal IT usage, and IT assets) on the adoption of IT-enabled green innovation (Sun & Sun, 2021).

In the context of green management, the RBV may be used to define the level at which managerial and technical information technology applications are utilized to promote green thinking both within and outside of organizational boundaries and to lessen environmental concerns. It can be applied in order to minimize the negative effects of these applications on the environment (Benzidia et al., 2021). The need for a solid IT infrastructure, as well as appropriate IT specialists and partnerships, in order to support IT-enabled business processes has been shown in a number of studies conducted in the past. IT resources play an essential part in the process of promoting IT-enabled green innovations since they make it possible for companies to create and put into practice a variety of green management systems all at once (Jena & Ghadge, 2021).

In the current study, IT human resources (IT-HR) relate to the level of technical and business expertise that IT staff members possess, allowing them to anticipate the development of future technologies and successfully utilize them to align business processes with activities that support the environment (Du et al., 2018). Businesses with excellent IT-HR are more likely to create dependable IT solutions that satisfy their business requirements more quickly than their rivals. Similarly, the right IT personnel may be deployed to take on particular responsibilities within and across SC companies. According to Shaar et al. (2022), the capacity of the IT staff to comprehend "what is" and "what may be" in IT initiatives in connection to environmental sustainability is a prerequisite for the successful implementation of e-GSCM. It is crucial to link corporate social responsibility to the achievement of environmental sustainability through multiple stakeholders (such as employees and SC partners). These factors suggest that IT resources can be crucial for achieving environmental performance. Thus, the current study proposes that:

H1: Information technology infrastructure resources have a positive relationship with environmental performance

H2: Information technology relationship resources have a positive relationship with environmental performance

H3: Information technology human resources have a positive relationship with environmental performance

Mediating Role of Internal Green Integration in the relationship between Information Technology Resources and Environmental Performance

A supply chain that incorporates green components into its operational procedures, including green materials management, green production, green manufacturing, green distribution/marketing, and green reverse logistics is referred to as green integration. The degree of mutual dependency, trust, communication, and coordination between the IT department and SC partners who can utilize IT applications effectively is the key element of IT-RR (Ryoo & Koo, 2013). The business is able to undertake collaborative learning exercises and stimulate green innovation thanks to integrated and synergistic IT-RR, improving the likelihood of supporting a significant e-GSCM deployment (Tran et al., 2020). Therefore, it is hypothesized that more IT-RR will boost the possibility of effective internal e-GSCM integration.

Software and other tools used to automate the human resources function in firms are referred to as "HR technology" or "human resources information technology." The following are all included: payroll and employee compensation, talent acquisition and management, performance management, and benefits administration (Popa et al., 2021). The term "human resource management" (HRM) refers to the processes of selecting, training, encouraging, and rewarding personnel. A firm's HRM team must strive to become competitive in the HR field by consistently providing educational and training programs for the staff to support the organization's personal and professional growth.

In the current study, IT-HR relate to the level of technical and business expertise that IT staff members possess, allowing them to anticipate the development of future technologies and successfully utilize them to align business processes with activities that support the environment. Businesses with excellent IT-HR are more likely to create dependable IT solutions that satisfy their business requirements more quickly than their rivals. Similarly, the right IT personnel may be deployed to carry out particular responsibilities within and across SC companies. The capacity of the IT staff to comprehend "what is" and "what may be" in IT initiatives in connection to environmental sustainability is a prerequisite for the successful implementation of e-GSCM. It is crucial to link corporate social responsibility to the achievement of environmental sustainability through multiple stakeholders (such as employees and SC partners). The success of green IT projects will be facilitated by businesses with IT staff who possess superior green expertise and IT solutions that can communicate environmental values to internal and external stakeholders (workers and SC partners, respectively). These ideas led us to the hypothesis that IT-HR enable businesses to achieve a seamless digital transition and expand the use of e-GSCM.

IT infrastructure resources (IT-IR) encompasses the company's common technical resources (such as computer platforms, databases, and networks for electronic communications), which are defined by factors like connection, interoperability, and modularity (Benzidia et al., 2021). They are the meticulously constructed technological pillars on which present and future IT applications are constructed. Since IT-IR offer a reliable foundation to support environmentally friendly activities, they are likely to result in the deployment of e-GSCM (Lin, 2022). As an illustration, IT infrastructure connections are a crucial link in creating cross-functional and cross-firm process integration, which subsequently makes it possible to align IT applications with green management initiatives. Additionally, the business may exchange and communicate any type of information thanks to compatible IT architectures, which makes it simple to incorporate the efficient flow of information into IT applications (Al-Sheyadi et al., 2019; Sahoo et al., 2022).

Companies with greater levels of internal environmental integration are more dedicated and driven to guarantee that the environmental performance (EP) of their suppliers is strong as well. They have a higher propensity to manage and oversee their suppliers and enhance the sustainability of their operations, safeguarding their reputations and reducing environmental threats (Shaar et al., 2022).

Businesses with well-integrated internal systems can effectively combine data and transfer knowledge from multiple business units. It is more practicable for them to incorporate elements related to external partners into their internal processes when communicating with suppliers (Waqas et al., 2021). This makes it easier to quickly and completely access the supplier's environmental data and to identify and categorize any environmental issues it may have. Businesses with a high internal green integration (IGI) level are better able to communicate to their suppliers the enormous benefits of environmental input. These manifest as an increase in financial profits and the fulfillment of client demands (Kalyar et al., 2019). The competitiveness of the product is improved; suppliers transition from being passive to active environmental collaborators; businesses proactively use green manufacturing; and suppliers are inspired (while also confirming their own commitment) to engage in green projects.

H4: Internal green integration mediates the relationship between information technology infrastructure resources and environmental performance

H5: Internal green integration mediates the relationship between information technology relationship resources and environmental performance

H6: Internal green integration mediates the relationship between information technology human resources and environmental performance

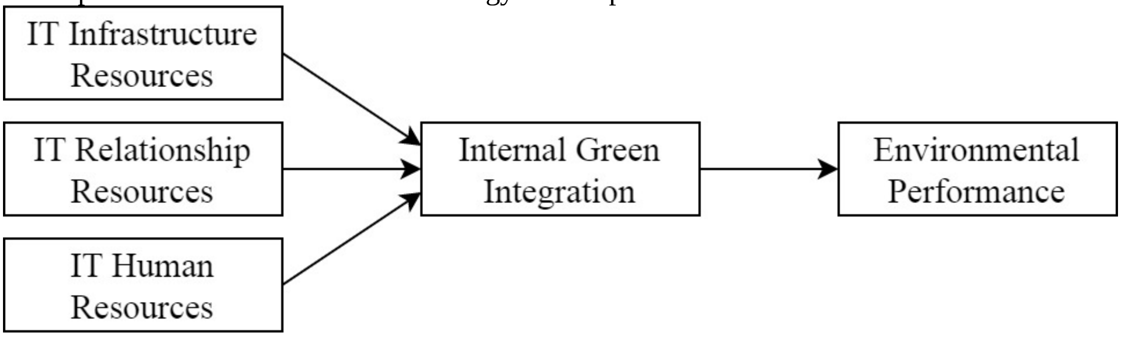

Fig. 1: Research Model

METHODS

Sample and data collection procedure

Data were collected from executives working in the textile sector in Punjab, Pakistan where green supply chain integration is being monitored. Initially, we approached 631 executives using the professional links of one of the authors. We received 512 accurate responses. Thus, the response rate of the study is 81.14%. Participation in the survey was voluntarily and the anonymity and confidentially of the respondents were ensured. The demographic statistics of the respondents revealed that 49.2% were male and 50.8% were female. 51.8% of respondents had experience of less than 10 years and 50.2% were middle managers while 49.8% were senior managers.

Measures

All study variables were measured using Likert scales ranging from 1 to 7 for IT-based variables and from 1 to 5 for green integration and environmental performance, where 1 was the lowest rank for the variable and 5 or 7 represented the highest rank.

IT- Infrastructure Resources

IT infrastructure resources were measured using the 5-item scale of Mao et al., (2016). One sample item used in the study was: "The quality of IT application and services (e.g., ERP and ASP) can meet the organizational needs." The Cronbach's alpha reliability of the scale was 0.864.

IT-Relationship Resources

IT relationship resources were also measured using the 5-item scale of Mao et al., (2016). One sample item used in the study was: "My organization has technology-based links with customers." The Cronbach's alpha reliability of the scale was 0.891.

IT-Human Resources

IT human resources were also measured using the 5-item scale of Mao et al., (2016). One sample item used in the study was: "The staff in my organization can evaluate and control IT projects." The Cronbach's alpha reliability of the scale was 0.754.

Internal Green Integration

Internal green integration was measured using the 5-item scale of Shah & Soomro (2021). One sample item used in the study was: "Our firm integrates environmental responsibility and objectives into various functional management systems (e.g., finance, human resource, and manufacturing)." The

Cronbach's alpha reliability of the scale was 0.902.

Environmental Performance

Environmental performance was measured using the 5-item scale of Shah & Soomro (2021). One sample item used in the study was: "Our firm has achieved a reduction in pollution and waste." The Cronbach's alpha reliability of the scale was 0.875.

RESULTS

Measurement model

The estimation of the relationship between indicators and constructs, as explained in the theory, relies on a measurement model based on the PLS algorithm (Hair, Hult, et al., 2017). The measurement model in PLS-SEM is comprised of construct, convergent and discriminant validities (Hair, Matthews, et al., 2017; Shiau et al., 2019). Table 1 shows the statistics for reliability and validity.

Table 1: Construct Reliability, Convergent and Discriminant Validity

	1	2	3	4	5	α	CR	AVE
1. Environmental Performance	**0.850**					0.902	0.928	0.723
2. IT Human Resources	0.260	**0.738**				0.754	0.825	0.545
3. IT Infrastructure Resources	0.301	0.136	**0.806**			0.864	0.902	0.649
4. IT Relationship Resources	0.332	0.198	0.491	**0.867**		0.891	0.924	0.752
5. Internal Green Integration	0.757	0.292	0.382	0.452	**0.817**	0.875	0.909	0.667

EP = Environmental Performance; ITHR = IT Human Resources; ITIR = IT Infrastructure Resources; ITRR = IT Relationship Resources; IGI = Internal Green Integration

Hair et al. (2011) recommended that alpha and CR coefficients should be greater than 0.70 and 0.80 respectively for acceptable internal consistency of the latent constructs, while AVE should be higher than 0.50 for considerable convergence and relatedness between indicators and constructs (Hair et al., 2013; Hair et al., 2014). In this regard, the above table shows that IT-HR has the lowest alpha coefficient of 0.754 and CR coefficient of 0.825; therefore, all constructs achieved acceptable reliability in the structural model. Moreover, IT-HR has the lowest AVE coefficient, which is 0.545 (i.e. higher than the recommended 0.50 threshold); thus, the indicators and constructs all achieved substantial relatedness in the structural model. Hence, adequate convergent validity was achieved in the model.

In the above table, the square roots of the AVE coefficients for latent constructs (bold diagonal values) are higher than their respective correlations with other constructs (non-bold values in the horizontal and vertical settings), and therefore, the shared variance of constructs is higher than their correlation with other constructs (Fornell & Larcker, 1981), manifesting no relation between latent constructs to substantiate their theoretical dissimilarity in the structural model (Hair et al., 2011, 2013; Hair et al., 2014). Hence, discriminant validity using the FLC method has been validated.

The above table shows that there was higher shared variance among the indicators (measured by their loadings) in the constructs with theoretical linkage than among their cross loadings with other constructs with weak or undefined theoretical linkage (Hair, Hult, et al., 2017; Hair et al., 2011, 2013). Therefore, discriminant validity using the cross-loadings method was achieved. Figure 2 shows the outer loadings data. All values are within the defined limits, indicating the validity of the construct.

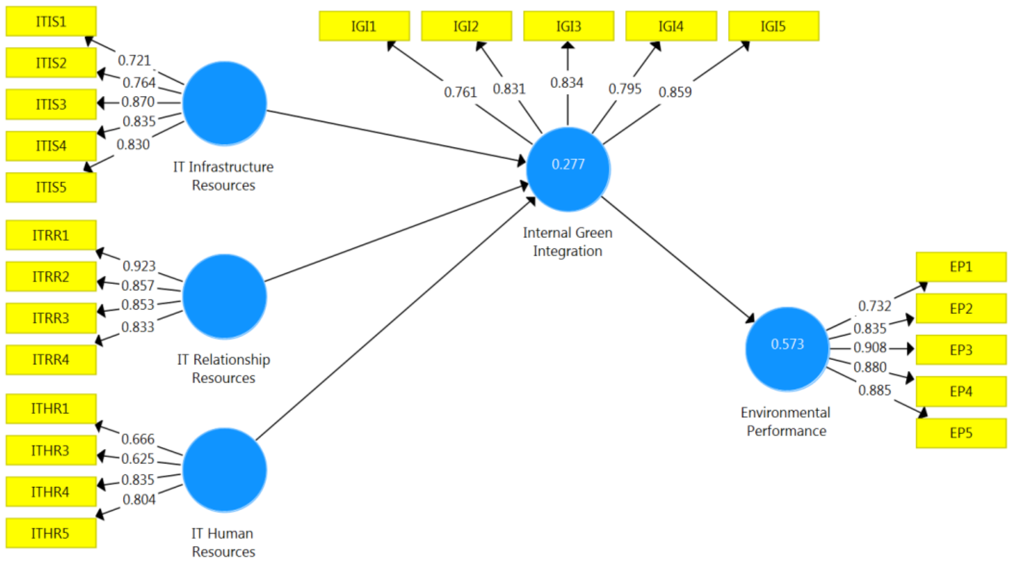

Fig. 1: PLS Algorithm using SmartPLS

Predictive power using R-Square

The statistical estimation of the predictability of the endogenous latent constructs in the structural model relies on predictive power based on R^2 and adjusted R^2 coefficients (Hair et al., 2011). Table 2 shows the predictive power for all endogenous constructs in the model.

Table 2: R-Square and Adjusted R-Square

	R Square	**R Square Adjusted**
Environmental Performance	0.573	0.572
Internal Green Integration	0.277	0.273

The above table demonstrates that environmental performance has a moderate predictive power of 57.3 percent in the structural model (Hair et al., 2011), while internal green integration has an acceptable predictability of 27.7 percent in the structural model (Hair et al., 2011).

Structural model

The statistical method for assessing the hypothesized relationship between latent constructs in the structural model for hypothesis-testing is referred to as a structural model in PLS-SEM (Hair, Hult, et al., 2017), based on a PLS bootstrapping technique with a recommended 5,000 subsamples and two-tailed analysis with a probability level of 5 percent (Hair et al., 2011).

Hypothesis-testing using direct-effect analysis

Table 3 provides the result of path analysis for hypothesis-testing of the direct-effect estimations based on PLS bootstrapping (Lee et al., 2011; Roemer, 2016).

The above table shows that IT human resources ($\beta = 0.202$; $p < 0.05$), IT infrastructure resources ($\beta = 0.200$; $p < 0.05$), and IT relationship resources ($\beta = 0.314$; $p < 0.05$) all have a significant positive effect on internal green integration while internal green integration ($\beta = 0.757$; $p < 0.05$) has a significant positive effect on environmental performance.

IT human resources ($\beta = 0.153$; $p < 0.05$) have a significant positive effect on environmental performance with the mediation of internal green integration. Similarly, IT infrastructure resources (β = 0.152; $p < 0.05$) have a significant positive effect on environmental performance with the mediation of internal green integration. Lastly, IT relationship resources (β = 0.238; $p < 0.05$) have a significant positive effect on environmental performance with the mediation of internal green integration.

Table 3: Path Analysis

	Estimate	S. D.	t-Stats	Prob.	Decision
ITHR -> IGI	0.202	0.034	5.899	0.000	Accepted
ITIR -> IGI	0.200	0.053	3.747	0.000	Accepted
ITRR -> IGI	0.314	0.040	7.794	0.000	Accepted
IGI -> EP	0.757	0.021	36.427	0.000	Accepted
ITHR -> IGI -> EP	0.153	0.027	5.750	0.000	Accepted
ITIR -> IGI -> EP	0.152	0.040	3.762	0.000	Accepted
ITRR -> IGI -> EP	0.238	0.031	7.558	0.000	Accepted

EP = Environmental Performance; ITHR = IT Human Resources; ITIR = IT Infrastructure Resources; ITRR = IT Relationship Resources; IGI = Internal Green Integration

Predictive relevance using Q-Square

The statistical measure for relevance of the endogenous latent constructs in the structural model is referred to as predictive relevance in PLS-SEM (Hair, Hult, et al., 2017). It is based on the PLS blindfolding technique with 7 omissions (Hair et al., 2011, 2013), as recorded in the table below.

Table 4: Predictive Relevance using Q^2

	Q Square
Environmental Performance	0.408
Internal Green Integration	0.180

Environmental performance has 40.8 percent (i.e. strong) relevance in the structural model (Hair et al., 2013), whereas internal green integration has 18 percent (i.e. moderate) relevance in the structural model (Hair et al., 2013).

DISCUSSION AND CONCLUSIONS

The sustainability of the supply chain industry and the health of our world depend on GSC practices. The current study examined the effect of IT resources on environmental performance and the mediating role of internal green integration among textile firms in Punjab, Pakistan. It investigated these effects since there is a noticeable gap in the relevant literature with reference to developing economies. The study proposed six hypotheses in total, with the theoretical background based on natural resource based view i.e. NRBV theory. All the hypotheses can be accepted based on the in-depth data analysis.

The findings of this research indicate that green integration has a considerable impact on environmental performance. Moreover, IT-IR exerts a substantial amount of pressure on environmental performance. The findings of this research indicate that IT-RR do, in fact, have a major impact on environmental performance. Environmental performance is also significantly impacted by IT-HR's role in the organization. According to the findings of this research, internal green integration has a significant effect upon EP. According to the results, green integration acts as a connector between IT-RR and EP. IGI acts as a mediator between EP and IT-HR at the very end of the process.

These results are in line with the theory and previous research. They are similar to those of Wang et al. (2015), who suggested that a firm's environmental performance is highly influenced by its IT technical infrastructure, IT HR resources and IT-business alignment. Likewise, Li et al. (2021) suggested that a firm's IT resources can influence its environmental performance. However, it is important to note that both these studies were conducted in China, and thus the results of our study also validate those from a different context.

IT resources play a crucial role in supporting the efficacy of information because they act as catalysts in the process of information production. Since the quality of the information produced by IT infrastructure heavily depends on IT resources, they are also occasionally referred to as information system elements. IT systems are crucial to the efficient and effective use of information resources, and they also determine the quality and security of information resources. IT combines multiple supply chain procedures carried out by many businesses. It expedites company operations and avoids bottlenecks. Businesses, particularly those in manufacturing, are getting closer to attaining on-time procurement, reduced inventory, and improved efficiency. As a result, IT is viewed as a crucial component of SCM because it offers visual and aural information, through which it is possible to absorb and analyze crucial data in order to make wise judgments.

The study's conclusions will be helpful to Pakistani businesses since they will provide guidance on how they can enhance their EP. The study shows that creating the right standards is essential since IT management is a crucial phenomenon for operations and has to be backed up by a support system in case of unanticipated events.

The knowledge base and applications of green integration are expanded by this research. First of all, it provides a more comprehensive conceptual framework for comprehending both the direct and indirect impacts of green integration on EP. Our findings clearly demonstrate that it is critical to optimize the interaction impact of IT-HR and relationship resources when enterprises are interested in improving their green performance by concentrating on the potent effects of these resources, which have generally been ignored by prior research. They also offer empirical proof that the relationship between IT-HR and EP is indirectly mediated by internal integration.

Even while scholars have acknowledged the significance of internal integration, conflicting results have made it difficult to fully understand how it relates to IT-HR. This study expands our knowledge of internal integration's mediating influence on the effects of EP, giving businesses additional alternatives for enhancing EP.

This also makes it easier to understand how infrastructure resource conditions affect EP. The empirical research used in this study also enables academics and practitioners to better comprehend how various green integration traits, indicators, and aspects affect an organization's success and may help them to compare the effect of profitability drivers across an organization that is integrating a green internal environment. Finally, the results can help managers understand the significance of internal factors and their impact on performance. Prospective managers will be aware of how important these factors are to their decision-making.

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ORIGINAL PAPER

A SYSTEMATIC LITERATURE REVIEW ON ADVANCES, TRENDS AND CHALLENGES IN PROJECT MANAGEMENT AND INDUSTRY 4.0

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ABSTRACT. Background: This review examines the concept of Industry 4.0, underscoring its genesis, integral technologies, implementation hurdles, and the imperative nature of sustainability. The successful transition to Industry 4.0 necessitates the comprehensive understanding and efficacious management of a multitude of intricate variables.

Methods: A Systematic Literature Review was undertaken and coupled with a bibliometric analysis to probe into the current status of Project Management and Industry 4.0 research. The stringent procedures employed encompassed a literature search, selection based on precise inclusion/exclusion criteria, and an in-depth analysis, culminating in the identification of future research opportunities.

Results: The findings reveal a burgeoning interest in project management and Industry 4.0, the dominance of conference papers and scholarly articles, an interdisciplinary approach to project management and Industry 4.0, global participation, and notable authors in the field. Moreover, content analysis facilitated the delineation of study topics concerning the transformation of the project manager's role in Industry 4.0, the adoption and utilization of digital technologies in project management during the Industry 4.0 era, success determinants for project management in the Industry 4.0 epoch, the adaptation and evolution of project management in light of Industry 4.0, the influence of digitalization on project management and sustainability, strategic project management methodologies in the context of Industry 4.0 technologies, and barriers impeding the implementation of Industry 4.0 technologies.

Conclusion: This study clearly shows that there is a rising interest in project management and Industry 4.0, with a specific emphasis on the application of digital technologies. It underscores the pivotal role of education and training in these novel technologies. Crucial success factors include maturity in project management, effective training, and adeptness in implementing Industry 4.0 components. The review uncovers opportunities for future research that could aid organizations and professionals in navigating the progressively more digitized landscape of their respective fields.

Keywords: Project Management, Industry 4.0, Digital Technology, Systematic Literature Review.

INTRODUCTION

Industry 4.0, a term first introduced in Germany in 2012, represents a strategic initiative to capitalize on emergent technological advancements, including cyber-physical systems, the Internet of Things (IoT), future industrial sectors, real-time collaboration, and the digitalization of manufacturing. At the inception of the Fourth Industrial Revolution or Industry 4.0, Enterprise Resource Planning (ERP) evolved as a vital component encapsulated within the Future of Factories

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(FoF) concept, which characterizes the technologies aligned with Industry 4.0.

Various studies have delved into multiple facets of Industry 4.0. For instance, Jardim et al. [2016] pinpointed the principal challenges and innovations pertaining to intelligent industrial production. Concurrently, Haddara & Elragal [2015] appraised the preparedness of ERP systems for FoFs, while Jin et al. [2017] fueled the discussion on process design management in the realm of human resources within a globalized context. This has fostered the emergence of virtual spaces in workplaces for customer interaction, bespoke on-demand manufacturing, and the circular economy. The goal of Industry 4.0 is to enable the integration and synergy of physical and digital realms. Ghobakhloo [2020] delivered a holistic perspective of the constituent elements of Industry 4.0 and their interdependencies, including smart project management, smart stakeholders, smart supplies, smart environmental sustainability, smart warehouses, smart products, smart customer integration, smart factories, and smart manufacturing [Valentin et al., 2018].

Kiraz et al. [2020] detailed nine elements influencing the current trends in Industry 4.0, among which market and consumer access is deemed most critical. These components include market and consumer access, data protection, processing and collective expertise, organizational culture, value chain and processes, IT architecture, risk and security, business models, products and services, data integration for analytics, leadership strategy, culture, and management. Within the prevailing competitive global climate, market and consumer access is perceived as the most influential element.

Even though Industry 4.0 technologies exist, their deployment relies on numerous variables, paradigm shifts, and changes in approach. If sustainability is not the central focus, the 4.0 revolution may lose its course and intensify environmental degradation and resource depletion. The true potential of Industry 4.0 can be realized when supply chains, intelligent machines, and specialized human resources are interconnected within a unified network, operating in real time within a circular economy [Ghimire et al., 2017]. Ozkan et al. [2020] illuminated the current challenges faced during the transition to Industry 4.0. Majumdar, Garg, & Jain [2020] recognized similar barriers in the textile and apparel industry, encompassing the lack of workforce training, inadequate understanding and commitment from top executives, insufficient government support and policies, gaps in research and development, high implementation costs, fear of change and failure, and poor integration and compatibility. Bag et al. [2020] documented the modifications required for the adoption of Industry 4.0. Ambitious plans like China's "Made in China 2025" aim to shift from the mass production of standardized goods to high-tech customizable products. In Germany, sustainable energy use, energy audits, management and monitoring systems, sales control, and energy integration are viewed as critical in the Industry 4.0 environment.

The purpose of this article is to offer an extensive overview of the nascent features and trends of Industry 4.0, highlighting important aspects related to its implementation while pinpointing potential advantages and challenges. Comprehending how to navigate this intricate environment is crucial given the complexities of implementing Industry 4.0 [Zhu & Mostafavi, 2017]. This article also scrutinizes the project management approach in engineering and probes into a variety of technological tools for implementation and integration. A successful transition to Industry 4.0 is contingent upon numerous variables, each one possessing its unique challenges and opportunities. Acknowledging these factors will enable industries to better equip themselves for this transformative shift, thereby enhancing efficiency, productivity, and sustainability [Benešová et al., 2019]. The insights and strategies elicited from this research review could serve as beneficial guidelines for corporations aiming to smoothly transition to Industry 4.0.

METHODOLOGY

To ensure credibility in research addressing a given problem, it is vital to utilize a methodology that comprises a series of transparent procedures [Kraus et al., 2022]. The Systematic Literature Review (SLR) has gained recognition as a gold standard in locating, selecting, and synthesizing published materials with the aim of addressing a pre-defined research question [Snyder, 2019]. Moreover, this methodology serves diverse functions ranging from charting the intellectual territory to pinpointing future research opportunities and shaping pertinent research questions [Borrego et al., 2014]. This is achieved through a stringent methodology that incorporates formulating the research question, defining inclusion and exclusion criteria, conducting literature search and selection, extracting and synthesizing data, assessing study quality and risk of bias, and ultimately, communicating and disseminating results [Snyder, 2023; Perez, 2019].

In alignment with the aforementioned, we applied the SLR methodology to examine the extant literature on Project Management and Industry 4.0. Furthermore, we undertook a bibliometric review as it provides the advantage of handling a substantial volume of published works and scrutinizing them to suggest future directions [Linnenluecke et al., 2019]. To assure the objectivity and reliability of the bibliometric review, a review protocol was devised, as shown in Table 1 [Kraus et al., 2022]. Figure 1 delineates the stages followed to execute the SLR, the specifics of which are described subsequently.

Table 1. Search protocol.

Protocol	Description
Database	Scopus, Web of Science (WOS)
Search item	Title, keywords and abstract
Keywords	**PM:** "project management*" OR "project management 4.0” **I4.0:** "Industry 4.0" OR "digital technolog*" OR "fourth industry" OR "I4.0"
Inclusion criteria	- Type of document: article, review, conference paper, book chapter, conference review - Language: English and Spanish - Knowledge area: Engineering, Management, Computer Science, Decision Sciences and Social Sciences.
Exclusion criteria	- Not aligned with Projects and Industry 4.0 - Written in a language other than English - Duplicates (same articles found in different databases)
Analysis tool	VOSViewer for bibliometric analysis
Data analysis	Bibliometric and evolution analysis of the use of digital tools and I4.0 in project management.

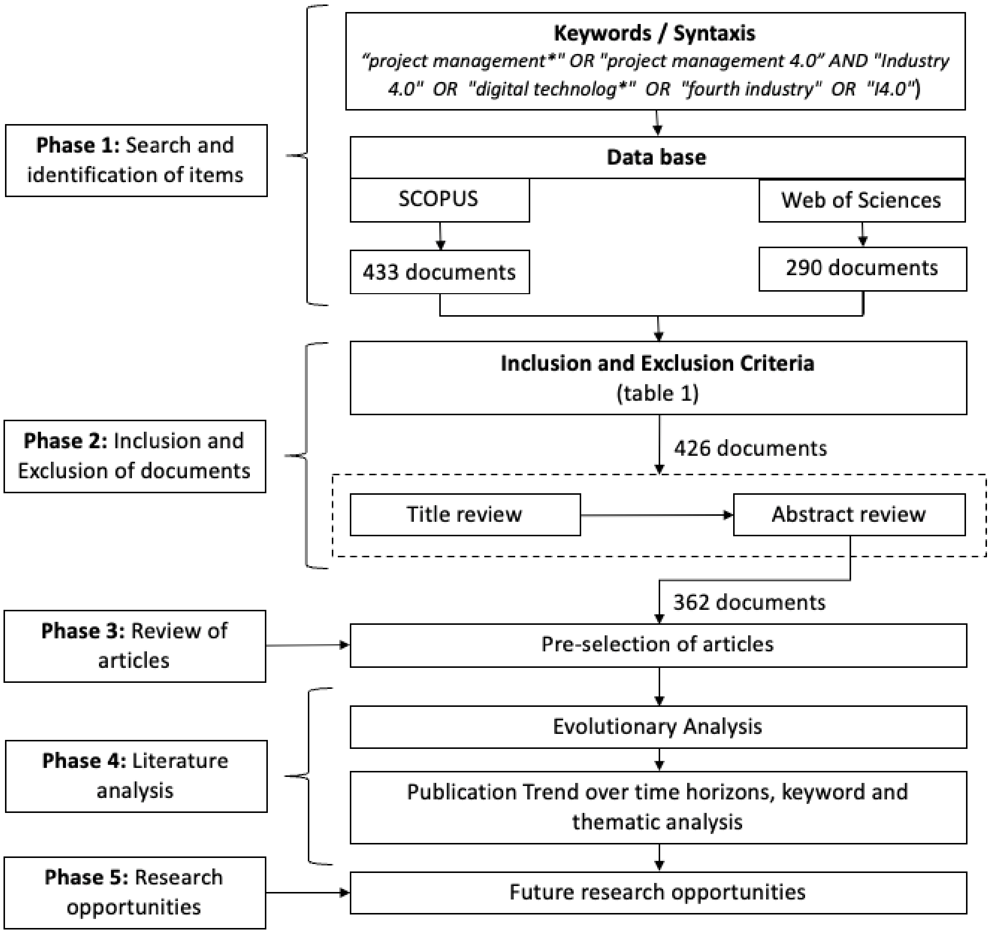

Fig. 1. SLR search methodology.

Phase 1: Search and identification of documents

Articles for review were extracted from the recognized academic databases Scopus and Web of Science. The keywords and syntax used were (TITLE-ABS-KEY ("project management*" OR "project management 4.0") AND TITLE-ABS-KEY ("Industry 4.0" OR "digital technolog*" OR "fourth industry" OR "I4.0"). This search was conducted during May 2023.

Phase 2: Inclusion/Exclusion Criteria

The keyword search led to the identification of 487 articles in Scopus, 290 articles in Web of Science. We applied the inclusion and exclusion criteria detailed in Table 1 to exclude unrelated articles and duplicates. This selection reduced the number to 426 articles. In addition, in line with the topic, we performed a selection of full abstracts to include the most relevant articles for the review. As a result, we shortlisted 362 articles for review and analysis.

Phase 3: Review of Shortlisted Articles

The shortlisted articles were critically analyzed and reviewed to understand the state of the research, development, and application of the I4.0 concept in project management to understand the progression of any cutting-edge research, salient issues, and evolution of the field.

Phase 4: Literature Analysis

Bibliometric and thematic analyses were conducted on the shortlisted articles. The bibliometric analysis allowed us to examine publication trends (by year and country), citation patterns, and keywords. We used VOSviewer© software to perform a keyword analysis to determine the frequency of co-occurrence of keywords. In addition, we identified, analyzed, and discussed the most salient PM and I4.0 themes.

Phase 5: Research Opportunities

Through the literature review, we identified research gaps. Based on these gaps, we defined the research opportunities presented in this section.

RESULTS AND DISCUSSION

Bibliometric analysis

Descriptive analysis was conducted to summarize relevant information about the publications shortlisted for this review study. The descriptive analysis provided a detailed understanding of publication trends over time, geographic locations, areas of expertise, and document types. In addition, we conducted a keyword analysis to gain insight into the most salient concepts discussed in the existing literature.

Figure 2 presents the publications of PM and I4.0 research over time. A total of 362 papers published between 1997 and May 2023 were identified. Interest in this field of knowledge was minimal until 2014. During the first few years, between 1 and 4 documents were published. In 2004, 10 publications were reported. After this year, until 2007, the literature begins to show a significant increase in publications. Then, in the years 2010 to 2022, 70% of the 362 documents reviewed were published.

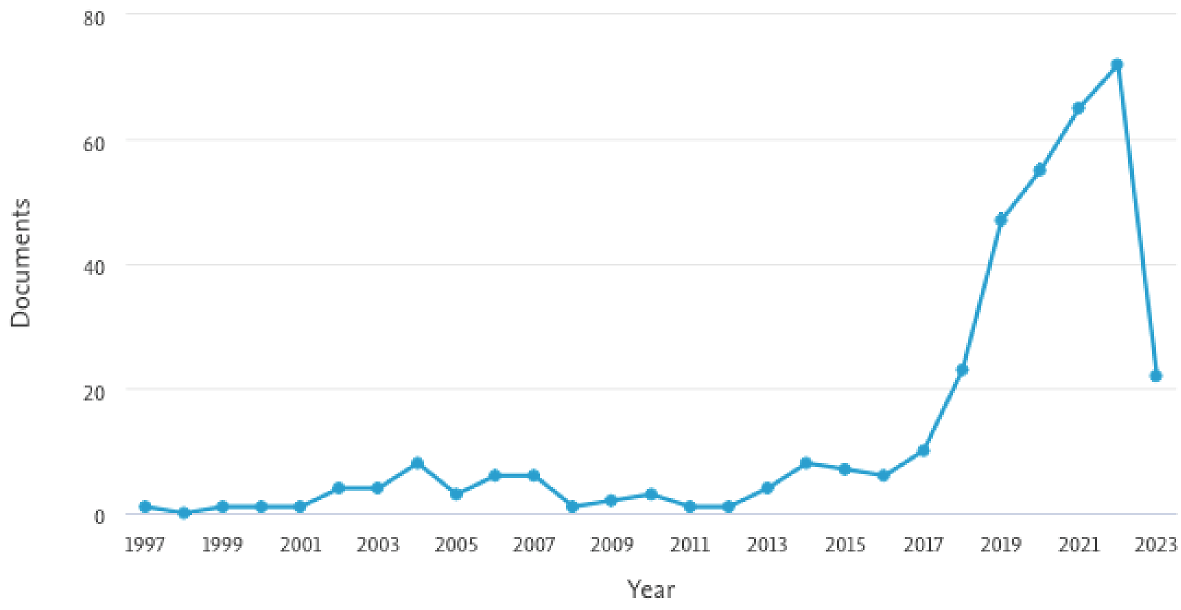

Fig. 2. Publications by year.

Figure 3a shows the distribution of the documents with respect to the type of document. In this area of study, conference papers predominate in more than half of all the publications. However, it is evident that scientific articles take a large share, with 30.4%, followed by reviews, with 6.6%. This represents a great opportunity to publish scientific studies in high impact journals. Figure 3b presents the distribution of documents by area of knowledge. This subject area is of interest to various areas of study, primarily from engineering, to materials science and chemical engineering.

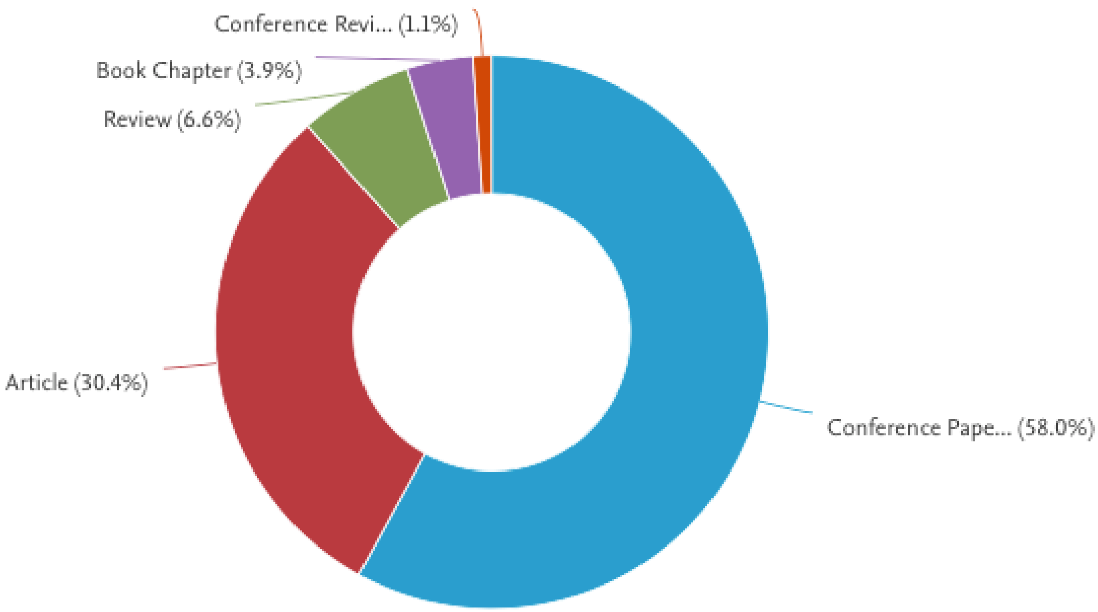

Fig. 3a. Publications by type of document.

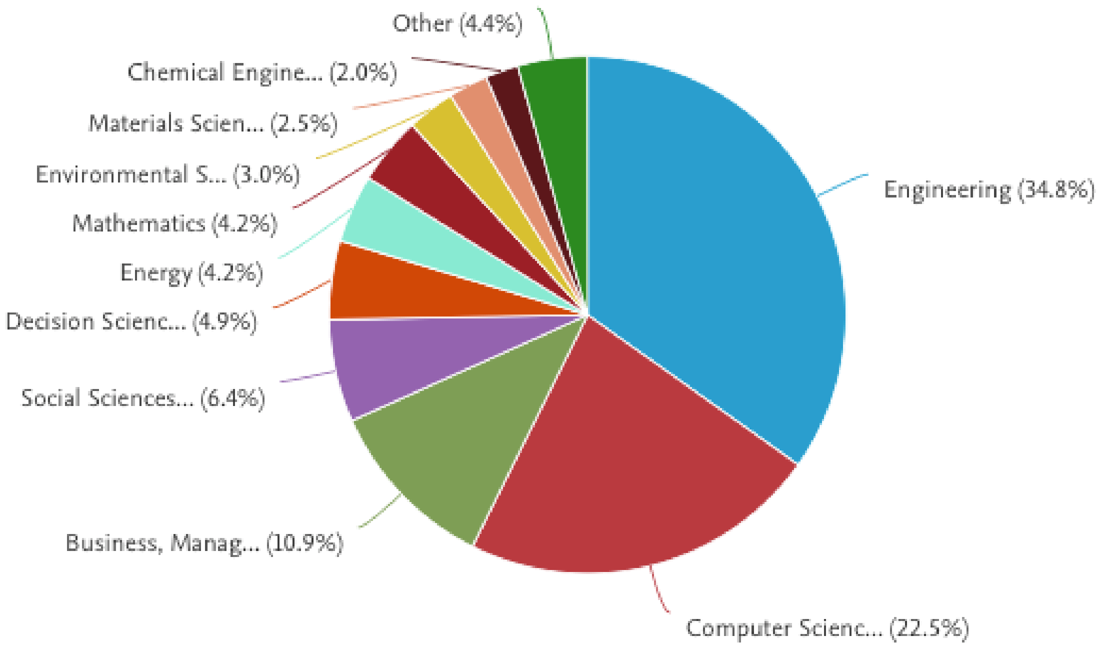

Fig. 3b. Publications by area of knowledge.

Contributions from 79 countries were counted in the studies analyzed. Figure 4 shows the 10 countries that published two or more articles. Authors from the United Kingdom and the United States contributed the most (87 studies), followed by China (40), Germany (27), and Australia (20).

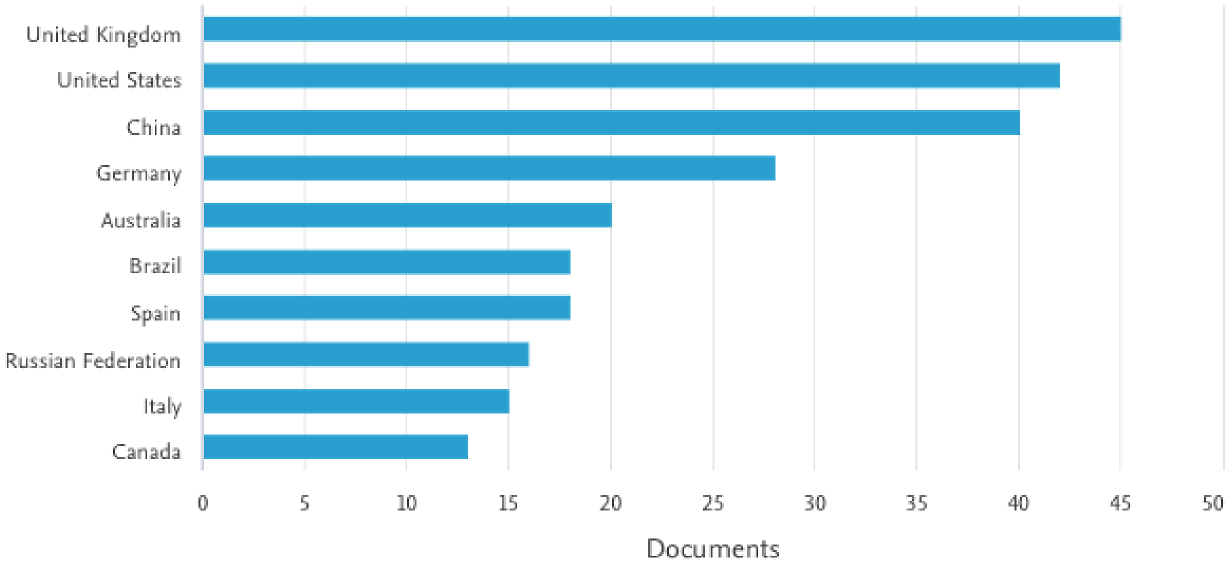

Fig. 4. Top 10 publications by country.

When analyzing the journals, it was found that the 362 documents were published in 232 different sources. In terms of refereed journals, Sustainability contributed 11 papers; however, the journal with the most citations is the International Journal of Production Research, with 202 citations in 1 article, followed by the Journal of Cleaner Production, with 3 articles. Table 3 presents the contribution of the top 10 journals.

Table 2. Top 10 journals with the highest number of publications.

Journal	Documents	Citations
Sustainability (Switzerland)	11	85
Automation in Construction	4	70
Engineering, Construction and Architectural Management	3	37
Journal of Cleaner Production	3	199
Journal of Information Technology in Construction	3	48
Journal of Manufacturing Technology Management	3	16
Operations Management Research	3	19
Sensors	3	18
Business Process Management Journal	2	15

Citation analysis

We performed a citation analysis of the 263 pre-selected studies. Table 3 shows the ten most cited papers focusing on the aspect of resilience within PM and I4.0. The reviewed papers have received a total of 2,911 citations (as of May 2023), with an average of 8 citations per article. It is notable that 55% of the citations correspond to article-type documents. It is evident that many highly cited papers have been published in the last 4 years. This could indicate the boom and interest in the implementation of I4.0 technologies in PM.

Table 3. Most cited documents.

Article	Citation	Average per year
Moeuf et al. (2020)	202	101
Bag et al. (2021)	147	147
Whyte et al. (2016)	120	20
Benner (2009)	90	6.92
Muñoz-la et al. (2021)	63	63
Pärn et al. (2018)	52	13
Chofreh et al. (2020)	52	26
Poirier et al. (2017)	51	10.2
Hassan (2013)	48	5.33
Vrchota et al. (2021)	48	48

Main authors.

Table 4 shows that Prof. Pellerin has contributed the most, with 6 publications on the subject. In terms of citations, Prof. Pal R. has been the most cited author, with 204 citations in only 1 published paper in the study area. However, among the authors with more than 1 published paper, author Liu Y. has 104 total citations and 52 citations per paper, followed by Prof. Jayaram, with a total of 101 citations and an average of 50.5 citations per paper.

Table 4. Main authors.

Author	Articles	Citation	Average per citation and article
Pellerin R.	6	248	41.3
Li Y.	5	13	2.6
Matt D.T.	5	31	6.2
Deschamps F.	3	5	1.7
Li T.	3	3	1.0
Marnewick A.L.	3	40	13.3
Marnewick C.	3	40	13.3
Narvel Y.A.M.	3	13	4.3
Oke A.E.	3	2	0.7
Perrier N.	3	38	12.7
Pellerin R.	6	248	41.3
Li Y.	5	13	2.6

Keyword analysis

Figure 5 presents the most used keywords and the co-occurrence between them. Four clusters of keywords of different colors are formed in the network. It is evident that project management, industry 4.0, digital technologies, construction industry, architectural design, information management, digital transformation, construction, decision making, life cycle, construction projects, engineering education, building information modeling, digital technology, human resource management, sustainable development, artificial intelligence, information systems, internet of things, BIM, competition, construction management, embedded systems, and information theory are the most used keywords in the documents. This indicates that these are some of the critical issues that have been addressed in PM and Industry 4.0 studies.

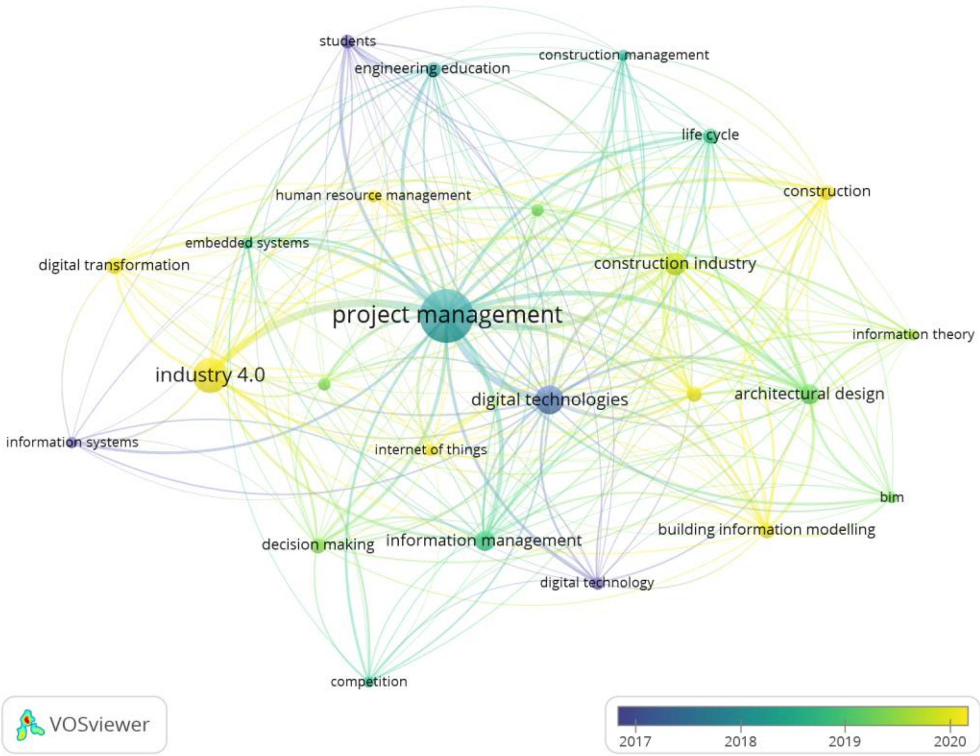

Fig. 4. Co-occurrence of keywords.

Content Analysis

A content analysis was carried out on the pre-selected articles to explore the progress of the studies within the FP and I4.0. The thematic lines that have been addressed by the different studies analyzed in the FP and I4.0 are detailed below.

Refashioning the Role of the Project Manager in Industry 4.0

The refashioning of the project manager's role in the era of Industry 4.0 entails alterations and demands that this role must confront amidst the digital revolution. The surveyed literature underscores education as a cardinal factor. Abushammala [2019] emphasizes the significance of university-level education in project management, specifically within civil engineering. The application of active learning methodologies and digital technology in a flipped classroom environment can enhance student performance. Amri et al. [2021] assert that academic and professional qualifications are pivotal in adapting to new Industry 4.0 methodologies. They further underscore the necessity for a heightened focus on the social dimension within sustainability studies related to Industry 4.0 as this influences the role of the project manager in construction [Albarracin-Rodriguez et al., 2023].

Various authors highlight the new skills and competencies necessary for the Industry 4.0 era. Ada et al. [2021] identify project management as the most crucial skill in the Industry 4.0 era, followed by financial management, technology skills, digital literacy, innovation, and creativity. Cabeças [2022] emphasizes the importance of outlining the appropriate profile of the project manager to confront this new reality, accentuating the relevance of new technologies and hybrid approaches to project management. Marnewick and Marnewick [2020a] contend that future project teams will incorporate both human and non-human entities (e.g., AI-enabled robots), necessitating novel competencies, especially in critical thinking and problem-solving.

Based on the refashioning of the project manager's role in Industry 4.0 and the research conducted by the cited authors, several prospects for future research have been identified:

- Evolution of project management in Industry 4.0.
- Impact of education on the reshaping of the project manager's role.
- Integration of sustainability into project management in Industry 4.0.
- Management of mixed project teams (human and non-human).
- Identification of competencies required for project management in Industry 4.0.
- Influence of social factors on project management in Industry 4.0.

Adoption and Application of Digital Technologies in Project Management in the Industry 4.0 Era

The adoption and application of digital technologies in project management within the era of Industry 4.0 are swiftly revolutionizing traditional operational methods. The referenced sources provide various case studies and perspectives on how these technologies are being incorporated within the construction sector and other industries. The awareness and employment of Cyber-Physical Systems (CPS) within Nigeria's construction industry are detailed by Adeosun & Oke [2022], identifying specific technologies as the most adopted within the construction sector. Attencia & Mattos [2022] scrutinize technology adoption within smart asset management and discuss factors that may influence the degree of technology adoption in asset management.

Atuahene et al. [2022] explore the benefits of Big Data within the construction industry, while Blackburn-Grenon et al. [2021] present a team-oriented workshop to harness organizational knowledge in identifying relevant artificial intelligence (AI) projects. Jasim et al. [2020] focus on the application of Artificial Neural Networks to enhance accuracy in estimating earned value indices in Iraqi road construction projects.

Research opportunities discerned from the information provided include:

- Comparative studies on the adoption of Cyber-Physical Systems (CPS) across different industries.
- Factors influencing technology adoption within smart asset management.
- Applications and benefits of Big Data in project management.
- Training and skills development for the adoption of AI technologies.
- Employment of Artificial Neural Networks in project estimation.
- Identification and surmounting of barriers to the adoption of digital technologies in project management.
- Case studies on the application of digital technologies in project management in the era of Industry 4.0.

Critical Success Factors for Project Management in the Industry 4.0 Era

This subject area investigates the pivotal elements that contribute to the success of digitization endeavors in the Industry 4.0 era while also examining the correlation between project management maturity, Industry 4.0 components, and business excellence. Fajsi et al. [2022] underscore the significance of project management maturity in attaining business excellence in the Industry 4.0 context. Kanski & Pizon [2023] propose that Industry 4.0 components can serve as indicators of project success, particularly in the implementation of digital enhancements. Moeuf et al. [2020] pinpoint the dearth of experience and a short-term strategic approach as potential risks for SMEs adopting Industry 4.0, emphasizing the essential role of training for project success. Pozzi et al. [2023] and Romagnoli et al. [2022] concentrate on the critical factors for the successful implementation of Industry 4.0 and suggest evaluation methodologies that focus on the external dimensions of the project, such as functionalities and the quality of outcomes. Contrarily, Vrchota et al. [2021] identify financing as a key factor for the sustainability of Industry 4.0 projects, linking the benefits of Industry 4.0 to sustainability. Opportunities for future research based on this discourse include:

- Analysis of the correlation between project management maturity and business excellence.
- Identification of Industry 4.0 components that impact project management success.
- Research on the critical elements for the successful adoption of Industry 4.0 within SMEs.
- Examination of the influence of training and skills development on the success of Industry 4.0 projects.
- Research on the success and sustainability factors of Industry 4.0 projects.
- Development of project evaluation methodologies in the context of Industry 4.0.
- Research on the correlation between Industry 4.0 project management and sustainability.

The Adaptation and Evolution of Project Management in the Context of Industry 4.0

The reviewed sources provide a multitude of perspectives on the adaptation and evolution of project management in the context of Industry 4.0. Aliev et al. [2007] and Kianpour et al. [2021] stress the necessity of integrating digital technology to augment efficiency and reliability in projects. Drobik [2000] and Piccione [2021] underscore the importance of effective planning and strategy, differentiating between E-business and E-commerce, and offering recommendations for strategy development. Frederico [2021], Gentner [2016], and Richard et al. [2021] propose frameworks for tailoring project management to the Industry 4.0 context, encompassing the use of agile and adaptive approaches, as discussed in the works of Kohnová et al. [2023] and Rane & Narvel [2021]. Lastly, Kinelski [2020] and Kianpour et al. [2021] explore digital transformation and continuous improvement as elements driving change in project management within Industry 4.0.

Opportunities for future research informed by these findings include:

- Best practices for integrating digital technology into project management.
- Effective planning and strategy approaches within the context of Industry 4.0.
- Tailoring project management to fit the Industry 4.0 landscape.
- Adoption of agile and adaptive methodologies within project management.
- Exploration of digital transformation and continuous improvement within project management.
- Case studies on the evolution of project management within the Industry 4.0 era.
- Training and competency requirements for project management within Industry 4.0.

Implications of Digitalization for Project Management and Sustainability

The progression of digitalization and Industry 4.0 continues to exert a significant influence on project management and sustainability, impacting professional practices, necessary competencies, and sustainability outcomes. Li et al. [2022] explore the way adoption of digital technologies, such as Building Information Modeling (BIM) and the Internet of Things (IoT), can enhance economic, environmental, and social sustainability within construction projects. They emphasize the crucial role of stakeholder collaboration in this context. Low et al. [2021] expose an escalating divergence between employer expectations and graduate skills in the Industry 4.0 epoch, proposing that alongside technical competencies, soft skills have grown in importance to adapt to novel work methodologies.

Marnewick & Marnewick [2020b] scrutinize the manner in which the Fourth Industrial Revolution is modifying the methods project teams utilize and manage. They contend that leadership styles must evolve, with servant leadership proving more apt in the context of implementing fresh technologies. Marnewick & Marnewick [2022] dissect the impact of digitization on IT project management, with their bibliometric analysis suggesting that while technologies are being employed to optimize project management processes, the discipline of project management has yet to be completely digitized. Olsson et al. [2021] inspect the application of 3D printing within construction projects, an innovation emblematic of Industry 4.0. While this technology can enhance the efficacy of construction processes, it also presents challenges, particularly concerning cost-efficiency. Vărzaru et al. [2022] evaluate how digitization is impacting project management, marketing, and decision-making processes, observing high acceptance of digitization in decision making, largely owing to the role of artificial intelligence in repetitive decision-making tasks. Walker & Lloyd-Walker [2019] investigate how shifts in the work environment are modifying the nature of project work and the requisite skills, predicting that non-routine work roles will become more interesting and rewarding, whereas routine roles are likely to be supplanted by advanced digital technology.

These studies highlight the necessity to adapt and evolve in response to the burgeoning influence of digitization and Industry 4.0 on project management and sustainability [Soledispa-Cañarte et al., 2023]. Both technical and soft skills, coupled with new leadership styles and collaboration methodologies, are increasingly crucial to navigate this novel landscape successfully [Albarracin-Rodriguez et al., 2023]. However, further research is required to thoroughly comprehend the implications of these trends and to guide practitioners and organizations as they adjust to them. Prospective research opportunities include:

- Digital technologies and sustainability.
- Skills for the digital age.
- Leadership styles in managing digitized projects.
- Comprehensive digitization of project management.
- Implementation of technological innovations and associated challenges.
- Digitization and decision-making.
- Changes in the work environment and their implications for project management.

Project Management Strategies and Industry 4.0 Technologies

The studies discussed herein delve into the interplay between project management and Industry 4.0 technologies and their impact across various industries, including the AEC (Architecture, Engineering, and Construction) sector and the brewing industry. Khodabakhshian A. et al. discuss how AI and machine learning techniques are being harnessed to improve risk management in construction projects, thus facilitating digitization and process optimization. Lima et al. [2023] posit that Lean project management (LPM) and soft skills are essential in tackling the uncertainties accompanying Industry 4.0, emphasizing the value these add to organizations in the digital transformation era. Sembin et al. [2021] investigate project management strategies in the context of digital transformation in Kazakhstan, underscoring the importance of effective implementation of Industry 4.0 innovations for sustainable development. Vrchota & Řehoř [2021] accentuate the need for innovation within project management and organizations, noting that effective project management can expedite change and innovation seamlessly and without errors. Wang [2015] elucidates how Industry 4.0 technologies are enhancing energy management in the brewing industry, particularly focusing on precise temperature control to optimize beer flavor. Whyte et al. [2016] discuss change management practices in organizations that handle large complex projects and depend on digital technologies, emphasizing the importance of configuration management in these contexts. Sipes [2006] discusses the use of the Global Information System (GIS) as a digital tool to determine geospatial data in design processes in architecture and interior design.

Barriers and Challenges Encountered in the Adoption of Industry 4.0 Technologies

An examination of the available information intimates that there are numerous obstacles and challenges to the implementation of Industry 4.0 technologies in the construction sector. Oke et al. [2023] concentrate on the hurdles that could impede the adoption of robotics and automation systems in developing nations, particularly in Nigeria. They delineate five primary barriers: the fragmented nature of construction processes, opposition from workers and unions, hesitation towards embracing innovations, lack of capacity and expertise, and insufficient backing from senior managers. Pärn et al. [2018] detail the "design clashes" encountered during the construction of an educational building in Birmingham, UK, and how these clashes can escalate project expenses. Wang et al. [2022] identify and evaluate obstacles to digital transformation in the engineering and construction sectors, with the top three being the "absence of industry-specific standards and laws," "lack of distinct vision, strategy, and direction for digital transformation," and "insufficient upper management support for digital transformation."

These barriers and challenges underline the necessity for improved training and education in emerging technologies, superior integration and coordination within construction processes, influential leadership willing to champion innovation, and policies and regulations that stimulate digital transformation within the construction industry. Emerging research opportunities include:

- Understanding and surmounting barriers to implementing robotics and automation systems.
- Resolving design conflicts in the implementation of Building Information Modeling (BIM).
- Overcoming barriers to digital transformation in engineering and construction.
- Studying case studies of success and failure in implementing Industry 4.0 technologies.
- Formulating policies and regulations to facilitate digital transformation in construction.

CONCLUSIONS

There has been a marked increase in the interest in and knowledge of the field of project management and Industry 4.0. An uptrend in research interest in project management and Industry 4.0 has been noted, with a particular emphasis on the application of digital technologies and the assimilation of these principles within the construction industry. Furthermore, this study suggests the existence of an active global research community and diverse topics of interest in this domain.

The systematic literature review illustrates a conspicuous trend in research towards the adaptation and evolution of project management within the context of Industry 4.0. Education and training in new technologies and project management methodologies emerge as pivotal elements to address the changes ushered in by digitalization. The transformation of the project manager's role in response to Industry 4.0 emerges as a recurring theme in the literature. The importance of education, training, and the identification of new skills and competencies to meet the new work paradigm proposed by Industry 4.0 is emphasized. The utilization and adoption of digital technologies in project management is rapidly altering traditional operational methodologies. Studies illustrate how these technologies are being integrated into various industries while concurrently identifying several challenges to their implementation.

Success factors for project management in the era of Industry 4.0 encompass project management maturity, training, and the aptitude to effectively implement Industry 4.0 components. Financial backing emerges as a crucial element for the sustainability of Industry 4.0 initiatives. Digitalization and Industry 4.0 are increasingly impacting project management and sustainability. To adapt to this evolving environment, project management professionals must develop technical and soft skills in addition to adopting new forms of leadership and collaboration. Lastly, the implementation of Industry 4.0 technologies presents several challenges, including resistance to change, absence of industry-specific standards and laws, and inadequate upper management support for digital transformation.

This review identifies several avenues for future research that could offer enhanced clarity and guidance as organizations and project management professionals navigate the increasing digitization of their sector. Concurrently, these avenues could help identify novel methods for fostering sustainability in project management. Project management in the era of Industry 4.0 is a rapidly progressing field laden with opportunities for new research and innovative practices.

The implications of this study extend to both academia and industry, providing insights that could shape future research directions and practical applications. This study maps the research terrain on the interaction between project management and Industry 4.0, which can be a guiding light for future research endeavors. It identifies critical areas needing further exploration, such as understanding and surmounting barriers to implementing robotics and automation systems, formulating policies and regulations to facilitate digital transformation, and effective strategies for training and education in new technologies. The cross-disciplinary nature of the study also encourages greater collaboration among researchers from fields like project management, engineering, information systems, and sustainability to yield holistic solutions.

The insights drawn from this study offer practical recommendations for the successful integration of Industry 4.0 technologies into project management. The highlighted success factors for project management in the Industry 4.0 era—such as project management maturity, adequate training, and effective implementation of Industry 4.0 components—can act as a guideline for industry practitioners. It underscores the need for robust leadership, a desire to champion innovation, and a shift in work paradigms, emphasizing the development of both technical and soft skills.

This study underscores the critical role of education and training in bridging the gap between current competencies and those required in the digitized industry landscape. This finding should prompt educational institutions and professional training organizations to reassess and restructure their curricula and training programs to meet the evolving needs of Industry 4.0.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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ORIGINAL PAPER

GLOBAL SCALE INTEGRATED LOGISTICS PERFORMANCE ANALYSIS AND ITS SPILLOVER EFFECT

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ABSTRACT. Background: Countries that are efficient in terms of logistics infrastructure have easy access to different markets in terms of production and foreign trade and thus achieve economic prosperity. In order to compare the performance of countries in logistics processes, there are international logistics indexes published by various organizations for different country categories. Each of these indexes is used to follow the performance of the logistics infrastructures of the countries and the logistics operations accordingly.

Methods: The aim of this study is calculation and comparison of the integrated logistics performance of 101 countries with the ROC-based WASPAS method and the presence of spatial autocorrelation between the obtained integrated logistics performance values by using four different international logistics indexes (Logistics Performance Index (LPI) (2018), Liner Shipping Connectivity Index (LSCI) (2021), Enabling Trade Index (ETI) (2016), and Availability and Quality of Transport Infrastructures (AQTI) (2016)) data.

Results: It has been determined that the top five countries with the highest integrated logistics performance are Singapore, Germany, China, Japan, England, and USA, respectively. On the other hand, Sierra Leone, Congo, Mauritania, Gabon, Liberia, and Madagascar are the weakest countries. Integrated logistics performance of a country is generally significantly affected by the logistics performance of the neighboring country, albeit limited. This is especially prevailing for USA, Canada, and Western Europe.

Conclusion: For the global integrated logistics performance analysis, countries with strong production capacity and logistics infrastructure are in first place, and there is a positive spatial autocorrelation in terms of integrated logistics performance among some countries in Western Europe and the Americas.

Keywords: Logistics Performance, Multi-Criteria Decision-Making Techniques, ROC, WASPAS, Spatial Autocorrelation

INTRODUCTION

Considering the similarity of production technologies and resources used today, it is known that the most crucial reason for preference for the customer is the price. So, while all other production conditions are almost the same, it is clear that the most challenging issue for businesses in terms of competition will be to provide price advantage. This is because customers now have the advantage of being able to supply any product they want from anywhere in the world. At this point, there is only one aspect that can provide a price advantage for businesses: logistics operations. According to "The World is Flat", Thomas L. Friedman [2006], while presenting the profile of the world of the future, there are ten forces that flattened the world, five of which are directly and five indirectly related to logistics. In this respect, logistics operations do not create value added for customers but are an important trigger for businesses.

Recently, the difference between the goods produced in the market and offered to the final consumer has decreased considerably. In other words, the functions of the products in the market have become closer to each other, and the technology contents that provide the similarities of these products have also converged. Although the trade of products with high value added in the international market is significant in terms of

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gaining profits, the fact that the information patterns related to these products converge and substitution characteristics increase necessitates the strategies based on price competition to be at the forefront. As a matter of fact, the global value chain created in the international production process operates based on high quality and price-oriented goals for the product [Mudambi and Puck, 2016; Ravenhill, 2014]. The strategies that emphasize supply chain and logistics operations are crucial for both businesses and countries. To be able to compete in the production and trade process, logistics operations need effective management, especially in transportation and warehousing processes. In other words, the effective management of the processes related to international logistics and logistics operations has a critical role in increasing the profitability of enterprises through foreign trade and countries achieving competitiveness in foreign trade as well. In addition, in international goods trade, international supply chain structuring has also turned into increasingly global logistics operations. Therefore, it is necessary for countries to determine multifaceted logistics operations and performance-based strategies in order to gain competitiveness and increase their income in international goods trade. In the new era business model, manufacturers often establish foreign factories in order to take advantage of tariff and trade concessions in foreign markets, low-cost direct labor, capital subsidies, and low logistics costs [Ferdows, 1997]. This situation brings manufacturers closer to different geographies and it provides convenience for them to use the geographical advantage of the country close to the supplier or where the production activity is carried out. The significant geographic distances on a global scale not only increase shipping costs, but also complicate many decisions due to increased inventory cost due to increased lead time in the supply chain [Meixell and Gargeya, 2005]. Today, about 70% of international trade involves global value chains. This means that services, raw materials, and components often cross borders many times and are shipped to consumers all over the world after being incorporated into final products [Alsamawi et al., 2020]. At this point, the role of logistics operations is large.

The strong inclusion of countries in international markets and their revenue generation depend on the extent to which they are affected by the global value chain. Therefore, strong inclusion of countries in the global value chain also requires strong logistics performance. In addition, being added to the complex value chain in the global supply chain can also affect the geographical location of the countries. With the liberalization of foreign trade, the international interaction of logistics operations has also increased. The transportation of a product that is produced and traded on a global scale to a certain region can be planted from other countries' geographical locations. As a matter of fact, this situation may have an effect on the advantageous logistics position of the countries to determine the logistics performance of the neighboring country. The logistics performance of a country is affected by its geography, and this may also affect the logistics performance of neighbor countries.

In recent years, the evaluation of logistics efficiency and performance has gained importance on a global scale. There are various indicators (Logistics Performance Index (LPI), Liner Shipping Connectivity Index (LSCI), Enabling Trade Index (ETI), and Availability and Quality of Transport Infrastructures (AQTI) e.g.) used to monitor the logistics performance of countries. These indexes, which show how effectively countries use their resources in terms of logistics, are also used to determine how strong these countries are, especially in foreign trade. These indexes can reveal the current situation of countries' logistics processes and have a key role in determining their policies regarding logistics operations in the future.

In the study, an integrated logistics performance ranking was conducted for 101 countries by using four different indexes (Logistics Performance Index (LPI), Liner Shipping Connectivity Index (LSCI), Enabling Trade Index (ETI), and Availability and Quality of Transport Infrastructures (AQTI)), which are used as a measure of international logistics performance. Rank Order Centroid (ROC) and Weighted Aggregated Sum Product Assessment (WASPAS) techniques were used to calculate the integrated logistics performance. The performance indexes were weighted using the ROC technique, and the WASPAS technique was used for ranking the countries. As far as is known in the literature, previous research on the logistics performance index have revealed that there is no study that employs different indices and methodologies in a cohesive manner as in this paper. In addition, using the scores obtained from WASPAS technique, which is calculated as an integrated performance measure in the study, the spatial relationship between the logistics performances of the countries was analyzed by using the Moran's I and Local Indicators of Spatial Association (LISA) method based on the geographic information system. Thus, it has been examined whether the logistics performances of the countries are also affected by other countries that have geographical contiguity. The objective of the spatial spillover effect analysis is to consider how improvements in logistics performance in one country can affect the performance of other countries within the same region or trade partner.

In the first section of the study following the introduction, some performance indexes calculated by different international institutions and determined for different areas of logistics were introduced. In the second section of the study, the previous studies were given as a literature review. In the third section, ROC, WASPAS, Moran' I, and LISA methods used in the study were introduced. In the fourth part, the data set, analysis, and findings were presented. In the last section, the results were discussed, and some suggestions were given.

VARIOUS LOGISTICS PERFORMANCE INDICATORS

One of the most important determinants of a country's global competitive advantage is the efficiency of logistics services in that country. An effective logistics management aims to increase efficiency and reliability, as well as to minimize logistics costs [Nordas et al., 2006].

The indexes and reports published by various international organizations are effective in terms of both seeing the logistics performance status of the countries in the world economy and determining their place among the countries in the region and revealing their visions [Yapraklı and Ünalan, 2017].

The most well-known criterion showing the logistics performance of countries at the global level is the logistics performance index (LPI) published by the World Bank. The index is published by the World Bank. The index is calculated through surveys obtained from experts in global logistics companies around the world. There are six dimensions to determine the logistics performance of countries: customs, infrastructures, ease of arranging shipments, quality of logistics services, tracking and tracing, and timeliness [Arvis et al., 2018].

The Liner Shipping Connectivity Index (LSCI), another measure of logistics performance on a global scale, has been published by the United Nations Conference on Trade and Development (UNCTAD) since 2004. The index in question shows how well countries are connected to global maritime transport networks in maritime transport. In the measurement made by UNCTAD, the year 2006 is accepted as 100 based. LSCI consists of five main components: the number of shipping companies, the amount of services provided by the companies, the number of ships, the container carrying capacity of the ships, and the size of the largest ship [UNCTAD, 2022].

Enabling Trade Index (ETI) has been published since 2008 by the World Economic Forum, through many academics, partner organizations and companies, to facilitate and evaluate trade. The index evaluates the countries' policies, infrastructure, institutions, and services that enable trade from the point of origin to the point of consumption. ETI is obtained by combining various factors that mediate enabling trade. These factors consist of seven pillars under the four main dimensions. These can be sorted into market access, border administration, infrastructure, and operating environment [WEF, 2016].

Another indicator is Availability and Quality of Transport Infrastructures (AQTI), which is one of the pillars of Enabling Trade Index. This pillar measures the availability and quality of domestic infrastructure for each of the four main modes of transport: road, air, railroad, and seaport infrastructures. Air connectivity and sea line connectivity are also assessed [WEF, 2016].

LITERATURE REVIEW

While numerous studies have been conducted to determine the logistics performance of nations, most have typically utilized the Logistics Performance Index or combined various data sets related to logistics functions. A few of these studies have utilized different multi-criteria decision-making methodologies, which are presented below.

Nguyen et al. [2022] evaluated the performance of maritime transport in 24 European Union countries by data envelopment analysis. In the study, the short sea shipping, energy consumption, containers, labor force, number, and gross tonnage of vessels were used as inputs and passenger and gross weight of goods transported were used as outputs. As a result, it has been determined that the countries with the best performance in maritime transport are Estonia, Croatia, and Latvia, respectively.

Mešić et al. [2022] compared the logistics performance of Western Balkan countries, which are Bosnia and Herzegovina, North Macedonia, Albania, Serbia and Montenegro, with the CRITIC and MARCOS methods, using the six criteria in the logistics performance index in 2018. According to the results, the most important criterion is shipment delivery within scheduled times, and it was stated that Serbia is the best country and Albania is the worst.

Işık et al. [2020] analyzed the logistics performance of 11 Central and Eastern European countries by analysis of variance and MABAC. It has been determined that the most important and least important criteria in logistics performance are timing and infrastructure, respectively. It has been determined that the country with the best performance in logistics performance is the Czech Republic, Poland, and Hungary, respectively.

Yalçın and Ayvaz [2020] evaluated customs management, infrastructure, international transportation, logistics service quality and adequacy, monitoring and tracking, and timing of Türkiye and Türkiye's four border neighbors Bulgaria, Greece, Georgia, and Iran by using Fuzzy AHP and Fuzzy TOPSIS methods. As a result of the analysis, it was found that the best performing countries are Türkiye, Iran, Bulgaria, Greece, and Georgia, respectively.

Kısa and Ayçin [2019] analyzed the logistics performance of OECD countries with the SWARA and EDAS methods. According to the results, the logistics service quality was found to be the most important criterion. In the ranking results, Germany, the Netherlands, and Sweden are in the first three places, while Latvia, Mexico, and Slovakia are in the last three.

Ulutaş and Karaköy [2019] examined the logistics performances of G20 countries using standard deviation and WASPAS methods. In the study, six factors in the logistics performance index were used for 2018. Germany, Japan, the United Kingdom, the United States, and France are the best countries.

Rezaei et al. [2018] weighted the six criteria in the logistics performance index with the Best-Worst Method by consulting 107 experts from six continents in 2016. Infrastructure was found to be the most important criterion in logistics performance, while traceability was the least important criterion. In addition, it has been suggested in the study that environmental effects, innovation, and investments in information technologies can be added to the logistics performance index.

Marti et al. [2017] aimed to propose a data envelopment analysis (DEA) approach to compute a synthetic index of overall logistics performance (DEA-LPI) and benchmark the logistics performance of the countries with LPI for 141 countries. It was determined that logistics performance depends largely on income and geographical area. High income countries are in the group of best performers, which is highly dominated by the EU.

Yu and Hsiao [2015] purposed to evaluate LPI using meta-frontier data envelopment analysis with assurance regions (Meta-DEA–AR) model. For conformity with the ranking of original World Bank LPI, the assurance region of each logistics indicator is obtained by a regression model. It has been found that the LPI rankings obtained by the proposed model are very comparable to those of World Bank LPI.

Considering previous literature, the logistics performance index published by the World Bank was generally used to measure the logistics performance of countries. In contrast to previous research, the current study seeks to integrated logistics performance of countries by using three different indexes including LPI.

METHODS

Rank Order Centroid (ROC)

There are different strategies for weighting the criteria affecting the decision. One of them is the ROC (Rank Order Centroid - Ranking Center Weights) technique, which was suggested by Barron and Barrett [1996] to be used in criterion weighting. The application steps of the ROC technique, which has reached a conclusion, are as follows by ranking only the criteria in order of importance and using the sort values with that array by decision makers [Ahn, 2011];

Ranking the decision criteria in order of importance; At this stage, n predetermined decision criteria, which are evaluated to affect the decision and are ranked in order of importance.

$$K_{r_1} > K_{r_2} > \cdots > K_{r_n} \qquad (1)$$

Calculation of criterion weight values; The criteria weights are determined by using Equation 2.

$$w_n = \frac{1}{N} * \sum_{k=n}^{N} \left(\frac{1}{r_k}\right) \qquad (2)$$

Weighted Aggregated Sum Product Assessment (WASPAS)

WASPAS (Weighted Aggregated Sum Product Assessment) was suggested by Zavadskas et al. [2012] to rank alternatives by using their criterion values and weights. The application stages of the WASPAS technique are as follows [Jahan, 2018];

Decision matrix has been prepared to represent m as the number of alternatives and n as the number of criteria. It is based on the criteria to be used in the analysis, as in Equation 3.

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \qquad (3)$$

Normalized decision matrix is prepared by using Equation 4 for utility-oriented criteria and Equation 5 for cost-oriented criteria.

$$x_{ij} = \frac{x_{ij}}{\underset{i}{max}\,(x_{ij})} \qquad (4)$$

$$x_{ij} = \frac{\underset{i}{min}\,(x_{ij})}{x_{ij}} \qquad (5)$$

In the next step, **weighted sum technique** is calculated by using Equation 6 and **weighted product technique** is calculated by using Equation 7.

$$WSM; Q_i^{(1)} = \sum_{j=1}^{n} x_{ij} * w_j \qquad (6)$$

$$WPM; Q_i^{(2)} = \prod_{j=1}^{n} (x_{ij})^{\pm w_j} \qquad (7)$$

In the last stage, **the compromised solution** is calculated by using Equation 8. The λ parameter in this equation can be determined freely by the decision maker.

$$WASPAS; Q_i = \lambda * Q_i^{(1)} + (1-\lambda) * Q_i^{(2)} \qquad (8)$$

In the compromised solution of the method, a ranking is made such that the alternative with the highest Q_i value is in the first place.

Spatial Autocorrelation: Moran's I and Local Moran's I Index

Spatial analysis methods are frequently used, especially in regional studies. Sample space data in regional studies belong to locations that represent a point in space. The basic principle underlying spatial data analysis is that observations that are close to each other are more related than observations that are far [Anselin, 1995; LeSage, 1999]. Spatial autocorrelation analyses show whether the variables are systematically and spatially distributed. In other words, it is about the covariance or correlation between data and contiguity observations. One of the statistics frequently used to measure spatial autocorrelation is Moran's I index. Moran's I value ranges from -1 to 1. A positive Moran's I value indicates clustering of similar values, and a negative Moran's I value indicates clustering of dissimilar values. A value of 0 indicates that there is no clustering. Moran's I index is calculated as shown in Equation 10 and Equation 11 [Anselin, 1995].

$$I = \frac{n}{S_0} \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \qquad (10)$$

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \qquad (11)$$

In the equations, n is the number of observations, w_{ij} is the spatial weight and thus is the sum of the spatial weights, x_i is the value of the variable belonging to the *i* location, x_j is the value of the variable to the *j* location, and $\overline{x}$ is the mean of the variable.

Moran's I statistic takes the entire data set in spatial autocorrelation and gives a single statistic for the interpretation of spatial autocorrelation. Moran's I does not include information on whether the dataset values are clustered with high or low values. On the other hand, local statistics allow for the analysis of the locations of the sample separately. For such an approach, spatial interaction is measured for each spatial unit (region) by using the Local Indicator of Spatial Association (LISA), and information about the type of this interaction can be obtained. The LISA index, which is used to determine the locations of possible clusters, is calculated as shown in equations 12 and 13 [Anselin, 1995].

$$I_i = \frac{x_i - \overline{x}}{S_i^2} \sum_{j=1}^{n} w_{ij} \qquad (12)$$

$$S_i^2 = \frac{\sum_{j=1}^{n} w_{ij}}{n-1} - X^2 \qquad (13)$$

The LISA index, which employed spatial autocorrelation at the local level, gives information about whether regions with high and low values are clustered or not. With this index, the existence of four separate relationships can be revealed. There are two categories of positive and negative autocorrelation. There are hot spot areas (High-High, HH) and cold spot areas (Low-Low, LL). In hot spot areas where regions with similar data cluster together, high-value regions of the relevant variable are clustered together. In cold spot areas, low-value regions of the relevant variable are clustered. For the negative correlation, there are two categories, the high-value region is surrounded by low-value neighbors, or low-value regions are surrounded by high-value regions. Spatially deviating regions can be detected with this type of autocorrelation [Fischer and Wang, 2011].

In the study, the spatial pattern was also taken into consideration when examining the country's performance in logistics processes. For this, the effect of spatial autocorrelation presented by the geographic information system was included in the analysis as well. Thus, it has been revealed whether the logistics performances of the countries are also affected by other geographical neighbors or contiguity countries. In the study, Moran's I test statistics were calculated for the integrated performance values obtained from WASPAS in examining the spatial autocorrelation. Then, the Local Moran's I index (LISA), which considers the autocorrelations of each country's logistics performance data, was calculated. Thus, the spatial significance of the clustering or outlier values of the data group in the analysis was also examined.

ANALYSIS AND FINDINGS

Integrated Logistics Performance by Various Logistic Index Values

In the study, an integrated logistics performance ranking was employed for 101 countries. Furthermore, in the analysis, the spatial autocorrelation tests were according to this performance score. The ROC-based

WASPAS method was used in the measurement of logistics integrated performance. The 101 countries included in the study and their compiled data are presented in Appendix 1, and the decision matrix was created based on this. The criteria and data year representing the indexes used for the integrated calculated performance measures are as follows:

- C1; Logistics Performance Index (LPI) (2018)
- C2; Liner Shipping Connectivity Index (LSCI) (2021)
- C3; Enabling Trade Index (ETI) (2016)
- C4; Availability and Quality of Transport Infrastructures (AQTI) (2016).

The ROC technique was used for the determination of criterion weight values. At this stage, a group of six experts, three of whom are academics and three of whom are industry professionals, was asked to rank the criteria in order of importance. In the study, the geometric mean of the ranking values made by the expert group was taken and a new and consensus ranking was obtained. These rank values are shown in Equation 1. Then, using Equation 2, the weight values of all the criteria were determined and presented in Table 1.

Table 1. Rank and Weight Values of Criteria According to Expert Group Opinions

Criteria	Academic Assessors			Sector Assessors			Geometric Average	Rank Values	Weight Values
	A1	A2	A3	IP1	IP2	IP3			
C1	1	1	2	1	2	1	1,2599	1	0,5208
C2	4	4	4	4	3	4	3,8127	4	0,0625
C3	2	2	3	3	4	2	2,5698	3	0,1458
C4	3	3	1	2	1	3	1,9442	2	0,2708

For the logistics efficiency ranking of the countries, a decision matrix has been prepared so that the criteria weight values obtained by the ROC technique will be used in WASPAS. Then, with the decision matrix presented in Appendix 1, the WASPAS process steps were followed. As a result, the efficiency scores, consisting of five different compromise solutions, and the rank values of the countries were obtained and are presented in Appendix 2 by giving different values to the compromise solution parameter (λ).

Singapore, Germany, China, Japan, England, and USA are the top five countries in logistics performance on a global scale. The common feature of these countries is that they have significant production and foreign trade volume. In addition, these countries have a strong infrastructure in logistics. These countries have an important place in the global value chain by continuing international production, trade, investments, and different stages of production processes in different countries as well.

According to the results of the analysis, the countries in the last place were Sierra Leone, Congo, Mauritania, Gabon, Liberia, and Madagascar. These countries do not have an important share in the global production and supply chain and are therefore behind in terms of foreign trade volume. In addition, the fact that the infrastructure of these countries for logistics operations is not developed can be shown as another reason for this result.

Integrated Logistics Performance and Spatial Autocorrelation

Using the WASPAS scores of the 101 countries included in the analysis, the existence of neighborhood relations between countries for integrated logistics performance was examined using Moran's I and Local Moran's I index. Thus, the spillover effect was investigated for logistics performance between geographically contiguity countries. In order to scrutinize the spatial autocorrelation, first the map of integrated logistics performance of the countries included in the analysis was drawn and presented in Figure 1. Accordingly, it is observed that countries with high logistics performance are clustered in North America and Western Europe.

In Figure 1, it is seen that the logistics performances of the countries may be related to the geographically neighboring countries. In other words, it is observed that there may be spatial autocorrelation between the logistics performances of countries. Univariate Moran's I test statistic was calculated in the examination of spatial autocorrelation using queen contiguity-based spatial weight matrix. According to Moran's I statistics, the logistics performance score of a country is affected by the logistics performance value of the neighboring country. Spatial correlation was I=0.3487, and this is statistically significant at the 5% level. As the value gets closer to 1, the importance of spatial lag increases. This finding indicates that the international logistics performance of a country is affected by the logistics performance of the neighboring country but is limited. (Fig. 2).

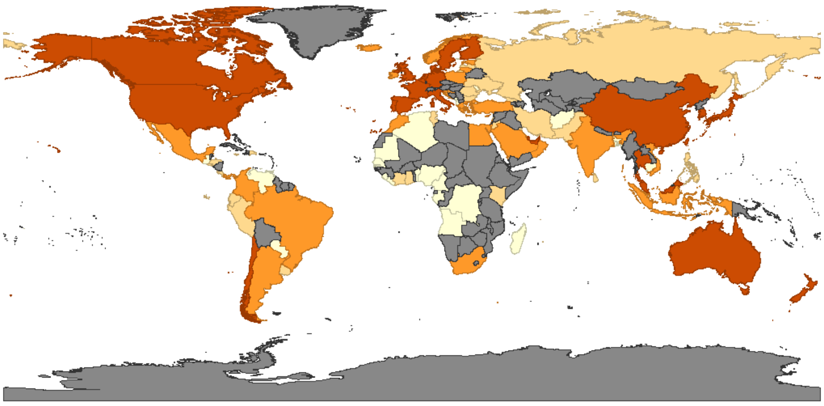
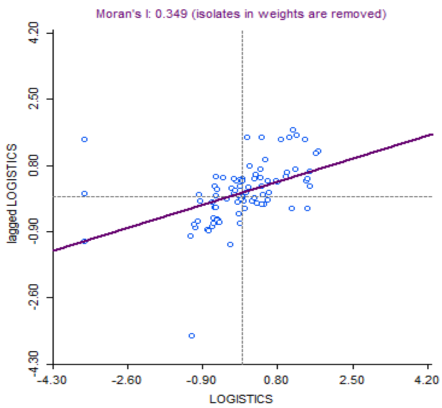


Fig. 1: Integrated Logistics Performance Clustering Map



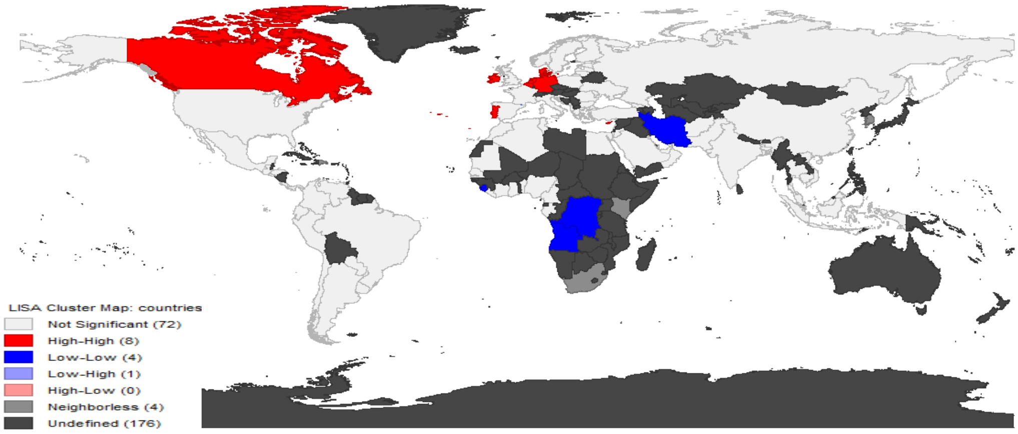
I: 0.3487	E[I]: -0.0119	Sd.: 0.1047	z-value: 3.4119	p-value: 0.005

Fig. 2: Moran's I Scatter Plot and Index

The clustering map of the Local Indicator of Spatial Association (LISA) for the Local Moran's I calculation, which deals with the lagged spatial effect from each country level, is given in Figure 3. Accordingly, a pattern is observed in which local spatial autocorrelation has a significant effect for some regions. For LISA index (spatial autocorrelation at the local level), the areas marked in red in the cluster map are located in the I. region of the Moran's I scatter plot, and the level of correlation is "high-high" (both high logistics performance of the country and high logistics performance of its neighbors). This spatial autocorrelation is especially valid and statistically significant (p=0.05) for some of the Americas and Western European countries. In other words, the integrated logistics performance value of the countries in this region positively affects other neighboring/contiguity countries and it is also determinant of logistics process efficiency. Clearly, Canada's logistics performance is also affected by America's high logistics performance. Similarly, Portugal and

Ireland are also positively affected by the logistics performance of their neighboring countries. The spatial autocorrelation effect of integrated logistics performance is positive for Germany, Belgium, Netherlands, and Denmark as well. It can be said that there is a spatial positive externality among logistics operations in these countries.

The blue colored regions on the map are in the III. region of Moran's I scatter plot. These regions shows that the level of correlation is "low-low" (both low logistics performance of the country and high logistics performance of its neighbors). This spatial autocorrelation is statistically significant (p=0.05) and limited for Congo and Liberia in Africa and Iran in the Middle East. On the other hand, there is no statistically significant autocorrelation in the cluster of countries which are in the II. and IV. regions of the Moran's I scatter plot with low logistics performance and high logistics performance, and vice versa. These regions are colored in grey.



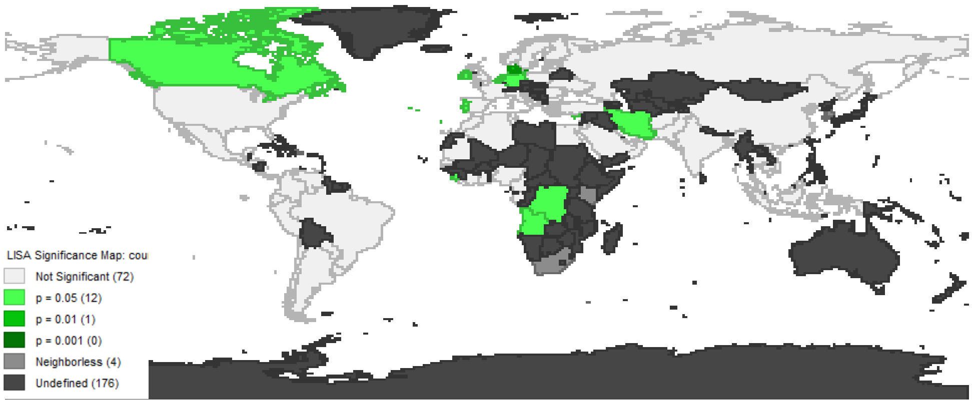


Fig. 3. LISA Clustering and Significance Map

DISCUSSION AND CONCLUSION

It is a well-established fact that logistics costs can exert a significant influence on the overall cost of products. Therefore, logistics is one of the critical issues that businesses can save on to maintain their competitiveness and to provide a sustainable production cycle [Ekici et al., 2016]. The fact that the countries have a strong infrastructure in terms of logistics also contributes positively to the competitiveness of the enterprises that produce goods subject to foreign trade and operate within the country. At the same time, this situation can contribute positively to the country's economic prosperity [Manavgat and Demirci, 2021]. Logistics performance is becoming more and more important for international trade in many countries [Martí et al., 2014]. In this respect, the creation of strategies for countries to come to the fore in terms of logistics on a global scale is one of the current issues.

In the study, integrated logistics performances were determined by using four basic index data prepared by different institutions to determine and monitor the logistics performances of countries. For this, the Logistics Performance Index, Liner Shipping Connectivity Index, Enabling Trade Index, and the Availability and Quality of Transport Infrastructures have been used as the criterion. Calculations were made for 101 countries with the ROC-based WASPAS technique. At the same time, using the WASPAS scores of the countries, spatial autocorrelation existence based on geographical information system has been analyzed by using Moran's I and Local Indicators of Spatial Association (LISA) method. Thus, it has been revealed whether the logistics performances of the countries are also affected by other geographical contiguity countries.

The outcome of the analysis shows that the top five countries with the highest integrated logistics performance are Singapore, Germany, China, Japan, England, and the USA, respectively. It can be inferred that these countries have a significant share in world trade and are sophisticatedly added to the global supply chain, so they have succeeded in managing their logistics infrastructure and processes relatively effectively. Earlier research has determined that these countries outperform others in terms of logistics performance as well and thus corroborating the outcomes of this study [Ulutaş and Karaköy, 2019; Kısa and Ayçin, 2019; Martí et al., 2017; Yu and Hsiao, 2015]. It has been found that Sierra Leone, Congo, Mauritania, Gabon, Liberia, and Madagascar are the weakest countries. These countries possess a relatively small proportion of the global production and supply chain; consequently, they lag behind in terms of foreign trade volume. Moreover, the inadequately developed logistics infrastructure in these countries reinforces this outcome.

Spatial pattern and autocorrelation were also considered in examining the performance of the countries covered in the study of logistics processes. When the effect of the neighborhood relationship of the countries on logistics performance was considered by using the scores obtained from WASPAS, it was determined that the integrated logistics performance of a country is generally significantly affected by the logistics performance of the neighboring country, albeit to a limited extent. According to the Local Indicator of Spatial Association (LISA), spatial autocorrelation is statistically significant and has a positive effect for some regions. This is especially the case for the USA, Canada, and Western Europe. The logistics performance of Canada is also affected by the USA's high logistics performance. Similarly, Portugal, Ireland, Germany, Belgium, Netherlands, and Denmark are positively affected by the logistics performance of their neighboring countries.

These results show that in Europe, it contributes to the improvement of the logistics performance of other neighboring countries, especially in the geography in which Germany is located. This is because the largest logistics market in the European Union is Germany (European Commission, 2015). Many countries, such as Slovenia, Belgium, Netherlands, and Slovakia are dependent on Germany through international trade, and the more effective functioning of these countries in the logistics market is affected by Germany's efficiency in logistics processes [Sternad et al., 2018]. Furthermore, the presence of Europe's 2nd and 3rd largest ports in Germany and Belgium also supports the ability of neighboring countries' international trade and logistics performance [World Shipping Council, 2019; Beysenbaev and Dus, 2020]. On the other hand, the fact that Germany has become the trigger of the global value chain in Central and Eastern Europe, increases Germany's role as an input supplier in the exports of Central and Eastern European countries (backward linkage rather than forward linkage) [Ambroziak, 2018]. This situation also supports the effect of the geographical neighborhood on logistics performance in the results of the study. Therefore, determining an inclusive or holistic logistics strategy between these countries would be a policy that would increase the strength of logistics network structuring.

Moreover, the negative spatial autocorrelation was also observed for very few African and Middle Eastern countries in the study. In the integrated logistics performance, the low logistics performance of Congo and Liberia in Africa and Iran's neighboring country in the Middle East has a significant effect on the low logistics performance of these countries. Another reason why these countries rank low in many logistics indicators (besides being behind in terms of economic and foreign trade volume) can also be stated as the fact that they are affected negatively by their neighbors geographically. This consequence may reveal that it would be more significative for them to turn to individual country-specific policies and even logistics strategies that would differ from geography rather than developing policies for the establishment of an integrated logistics network system based on geographical contiguity among these countries.

On the other hand, the limits of the study can be expressed for different perspectives. The analysis relies heavily on the availability and quality of data, which may be limited in some regions or countries. The measurement of integrated logistics performance has been attempted on a broad scale encompassing many countries, but incorporating data from countries missing data would strengthen global-scale analysis. Furthermore, the analysis solely depicts the current scenario, and it could be worthwhile to track the trend of logistics performance by contrasting the findings with past or future data. The analysis may not capture all aspects of logistics performance well, such as environmental sustainability and social responsibility for countries. Additionally, the spillover effects may not consider all potential impacts on different stakeholders, such as between consumers and local communities in terms of logistics performance.

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Appendix 1. Decision Matrix

No.	Countries	C1	C2	C3	C4
1	Albania	2,6596	4,3941	4,5100	2,6400
2	Algeria	2,4481	12,4657	3,5100	3,3330
3	Argentina	2,8870	34,2050	3,9800	4,0748
4	Australia	3,7514	36,6750	5,1000	4,8700
5	Bahrain	2,9348	27,9310	4,7900	4,8724
6	Bangladesh	2,5766	14,5477	3,4800	3,0720
7	Belgium	4,0391	87,9031	5,4500	5,2500
8	Benin	2,7499	20,4112	3,4800	2,6900
9	Brazil	2,9858	37,4589	3,8000	4,1408
10	Brunei Darussalam	2,7066	5,9573	4,2700	3,3900
11	Bulgaria	3,0340	7,7913	4,5400	3,1200
12	Cambodia	2,5786	8,8061	3,9600	3,1729
13	Cameroon	2,5955	19,7007	3,2000	2,4200
14	Canada	3,7267	48,0055	5,1500	5,2900
15	Chile	3,3171	36,6099	5,2600	4,5844
16	China	3,6051	168,4928	4,4900	5,0456
17	Colombia	2,9416	49,4777	4,1000	3,7550
18	Congo, Dem. Rep.	2,4284	4,7795	3,0300	2,0300
19	Costa Rica	2,7917	24,2429	4,5200	2,5700
20	Côte d'Ivoire	3,0823	20,2474	3,8700	3,6700
21	Croatia	3,1041	33,5668	4,7600	3,6600
22	Cyprus	3,1508	17,5659	4,6100	3,8400
23	Denmark	3,9919	46,0720	5,4200	4,8800
24	Dominican Rep.	2,6618	40,4564	4,2000	3,8200
25	Ecuador	2,8816	37,8637	4,1400	3,8766
26	Egypt, Arab Rep.	2,8249	66,9717	3,7200	3,9899
27	El Salvador	2,5755	8,1176	4,2500	3,1500
28	Estonia	3,3116	10,3838	5,3200	3,8400
29	Finland	3,9691	14,8988	5,6000	4,8900
30	France	3,8445	76,4629	5,3700	6,1300
31	Gabon	2,1619	12,6817	3,2400	2,4900
32	Gambia, The	2,4012	5,8825	3,9500	3,2200
33	Georgia	2,4428	6,0850	4,8000	3,3500
34	Germany	4,2014	84,4317	5,4900	6,0500
35	Ghana	2,5653	38,0037	3,9300	3,4557
36	Greece	3,2046	60,3570	4,5500	3,8600
37	Guatemala	2,4146	35,8639	4,3200	2,7000
38	Honduras	2,6039	11,9106	4,0800	3,1100
39	Hong Kong SAR	3,9201	92,9344	5,6600	6,4000
40	Iceland	3,2250	6,9932	5,2700	3,9400
41	India	3,1766	59,4728	3,9100	4,1500
42	Indonesia	3,1501	33,0762	4,3000	3,8977
43	Iran, Islamic Rep.	2,8527	31,1522	3,1600	3,5516
52	Kuwait	2,8612	10,4070	4,0700	4,1739
53	Latvia	2,8099	9,6777	4,8600	3,7200
54	Lebanon	2,7169	40,7662	4,0300	3,6873
55	Liberia	2,2292	6,5652	3,5300	2,6700
56	Lithuania	3,0175	18,1860	5,0100	3,9400
57	Madagascar	2,3894	7,9261	3,8000	2,1600
58	Malaysia	3,2209	99,0150	4,9000	5,1645
59	Malta	2,8138	56,3857	4,9500	3,8600
60	Mauritania	2,3311	7,4742	3,1800	2,2200
61	Mauritius	2,7330	31,3259	4,8900	3,7400
62	Mexico	3,0514	47,6724	4,5500	4,2938
63	Moldova	2,4559	0,6354	4,2000	2,7400
64	Montenegro	2,7456	4,9197	4,4600	2,7300
65	Morocco	2,5397	69,2554	4,6000	4,3211
66	Netherlands	4,0193	91,2893	5,7000	4,3300
67	New Zealand	3,8756	29,9973	5,2700	4,0300
68	Nigeria	2,5321	21,6948	3,2500	3,0552
69	Norway	3,6966	10,5649	5,2700	3,7000
70	Oman	3,1968	59,4869	4,6700	4,6307
71	Pakistan	2,4192	37,6157	3,5100	3,2734
72	Panama	3,2760	50,7336	4,5200	4,5100
73	Paraguay	2,7823	1,8508	3,8600	3,2693
74	Peru	2,6932	40,0014	4,5400	3,6319
75	Philippines	2,9037	25,6278	4,1300	3,4534
76	Poland	3,5395	51,9434	4,9600	3,8800
77	Portugal	3,6432	56,7627	5,0100	4,7500
78	Qatar	3,4742	39,1696	4,7800	5,1484
79	Romania	3,1186	26,6299	4,6100	2,9800
80	Russian Fed.	2,7569	34,4747	3,7900	4,4006
81	Saudi Arabia	3,0110	70,0976	4,3300	4,7666
82	Senegal	2,2524	17,2524	3,9700	3,0000
83	Sierra Leone	2,0780	6,7336	3,2500	2,5500
84	Singapore	3,9961	112,241 0	5,9700	6,2800
85	Slovenia	3,3148	34,4841	4,9600	3,6400
86	South Africa	3,3761	40,0156	4,5200	4,6686
87	Spain	3,8313	90,7593	5,2800	6,0900
88	Sri Lanka	2,5979	71,5236	3,9000	3,9366
89	Sweden	4,0529	48,1324	5,6100	4,8100
90	Taiwan, China	3,5997	84,9041	4,9200	5,2200
91	Thailand	3,4111	64,5727	4,4500	4,4349
92	Trini. & Toba.	2,4156	15,3668	3,8600	3,0100
93	Tunisia	2,5695	5,6920	4,0200	3,6679
94	Turkey	3,1458	61,3270	4,5200	4,4827

44	Ireland	3,5104	12,4619	5,2700	4,1100	95	Ukraine	2,8302	28,4272	3,9700	3,9104
45	Israel	3,3078	41,6096	4,9900	4,1600	96	Uni. Arab Em.	3,9564	75,3083	5,2300	5,9913
46	Italy	3,7392	75,5442	4,9100	4,7900	97	Uni. Kingdom	3,9871	90,2067	5,5200	5,7300
47	Jamaica	2,5187	35,0179	4,0300	3,3800	98	United States	3,8851	99,1369	5,2400	6,0800
48	Japan	4,0257	73,9028	5,2800	6,1000	99	Uruguay	2,6851	32,7657	4,3700	4,1066
49	Jordan	2,6880	33,9628	4,7300	4,0646	100	Venezuela, RB	2,2292	8,9891	2,8500	2,9892
50	Kenya	2,8149	17,3683	4,2000	3,7613	101	Vietnam	3,2740	76,7531	4,2600	4,0826
51	Korea, Rep.	3,6122	109,2519	5,0400	5,7100	**Criteria Weighs**		**0,5208**	**0,2708**	**0,1458**	**0,0625**

Appendix 2. WASPAS Scores and Ranking

Countries	λ = 0,00		λ = 0,25		λ = 0,50		λ = 0,75		λ = 1,00	
	Score	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
Albania	0,4739	92	0,4937	90	**0,5135**	**89**	0,5334	85	0,5532	83
Algeria	0,4975	86	0,5068	87	**0,5162**	**88**	0,5255	88	0,5349	87
Argentina	0,6210	52	0,6258	53	**0,6306**	**53**	0,6354	51	0,6402	51
Australia	0,7778	20	0,7857	20	**0,7936**	**20**	0,8014	20	0,8093	20
Bahrain	0,6669	40	0,6745	41	**0,6821**	**39**	0,6897	39	0,6974	40
Bangladesh	0,5040	82	0,5129	84	**0,5219**	**86**	0,5308	86	0,5398	85
Belgium	0,8797	10	0,8820	10	**0,8842**	**10**	0,8864	10	0,8886	10
Benin	0,5137	79	0,5221	79	**0,5305**	**81**	0,5389	83	0,5473	84
Brazil	0,6340	46	0,6385	46	**0,6431**	**49**	0,6476	49	0,6521	49
Brunei Darussalam	0,5174	76	0,5344	75	**0,5515**	**75**	0,5685	73	0,5855	72
Bulgaria	0,5509	73	0,5687	71	**0,5864**	**70**	0,6042	69	0,6219	64
Cambodia	0,5023	84	0,5152	82	**0,5281**	**82**	0,5410	82	0,5539	82
Cameroon	0,4774	90	0,4855	93	**0,4935**	**93**	0,5016	93	0,5096	93
Canada	0,8073	17	0,8128	17	**0,8184**	**16**	0,8239	16	0,8295	17
Chile	0,7209	27	0,7275	27	**0,7341**	**26**	0,7407	25	0,7473	26
China	0,8306	14	0,8311	14	**0,8316**	**15**	0,8321	15	0,8326	16
Colombia	0,6304	48	0,6333	50	**0,6362**	**50**	0,6391	50	0,6421	50
Congo, Democratic Republic	0,3993	101	0,4151	100	**0,4310**	**100**	0,4469	100	0,4627	99
Costa Rica	0,5370	74	0,5463	74	**0,5556**	**74**	0,5649	74	0,5742	75
Côte d'Ivoire	0,6019	60	0,6113	57	**0,6207**	**57**	0,6301	55	0,6394	52
Croatia	0,6422	44	0,6487	44	**0,6553**	**45**	0,6619	45	0,6684	47
Cyprus	0,6267	50	0,6381	47	**0,6495**	**46**	0,6609	46	0,6722	45
Denmark	0,8226	15	0,8297	15	**0,8367**	**14**	0,8438	14	0,8509	14
Dominican Republic	0,5957	64	0,5991	64	**0,6025**	**65**	0,6059	68	0,6092	69
Ecuador	0,6195	53	0,6237	54	**0,6280**	**54**	0,6322	54	0,6364	53
Egypt, Arab Republic	0,6304	47	0,6315	51	**0,6326**	**52**	0,6337	53	0,6347	56
El Salvador	0,5036	83	0,5175	81	**0,5315**	**79**	0,5455	81	0,5594	80
Estonia	0,6355	45	0,6534	43	**0,6712**	**42**	0,6890	40	0,7068	36
Finland	0,7684	22	0,7866	19	**0,8048**	**19**	0,8231	17	0,8413	15
France	0,8845	9	0,8872	9	**0,8900**	**9**	0,8928	9	0,8955	8
Gabon	0,4263	97	0,4341	97	**0,4418**	**98**	0,4495	99	0,4572	100
Gambia, The	0,4736	93	0,4884	91	**0,5031**	**91**	0,5179	91	0,5326	88
Georgia	0,4980	85	0,5145	83	**0,5311**	**80**	0,5476	78	0,5641	79
Germany	0,9318	2	0,9344	2	**0,9370**	**2**	0,9397	2	0,9423	2
Ghana	0,5611	71	0,5644	72	**0,5677**	**72**	0,5710	72	0,5743	74
Greece	0,6826	35	0,6855	37	**0,6884**	**37**	0,6913	38	0,6941	41
Guatemala	0,5137	78	0,5184	80	**0,5231**	**85**	0,5277	87	0,5324	89
Honduras	0,5139	77	0,5250	77	**0,5362**	**77**	0,5473	79	0,5585	81
Hong Kong SAR, China	0,9221	3	0,9240	3	**0,9258**	**3**	0,9277	3	0,9295	3
Iceland	0,6150	54	0,6357	49	**0,6564**	**44**	0,6771	43	0,6978	39
India	0,6772	36	0,6797	38	**0,6821**	**40**	0,6845	42	0,6870	43
Indonesia	0,6480	42	0,6542	42	**0,6604**	**43**	0,6666	44	0,6727	44
Iran, Islamic Rep.	0,5715	69	0,5768	70	**0,5821**	**71**	0,5874	71	0,5927	71

Countries	λ = 0,00		λ = 0,25		λ = 0,50		λ = 0,75		λ = 1,00	
	Score	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
Ireland	0,6740	38	0,6911	35	**0,7082**	**33**	0,7253	31	0,7425	29
Israel	0,7013	33	0,7068	31	**0,7124**	**31**	0,7179	33	0,7234	33
Italy	0,8043	18	0,8067	18	**0,8092**	**18**	0,8117	19	0,8142	19
Jamaica	0,5516	72	0,5554	73	**0,5592**	**73**	0,5629	75	0,5667	77
Japan	0,9006	4	0,9038	4	**0,9071**	**4**	0,9103	4	0,9136	4
Jordan	0,6128	56	0,6180	56	**0,6231**	**56**	0,6282	57	0,6334	58
Kenya	0,5794	68	0,5888	68	**0,5983**	**68**	0,6077	67	0,6172	65
Korea, Rep.	0,8510	11	0,8515	11	**0,8520**	**11**	0,8525	12	0,8531	13
Kuwait	0,5794	67	0,5932	67	**0,6070**	**63**	0,6208	60	0,6346	57
Latvia	0,5683	70	0,5833	69	**0,5982**	**69**	0,6131	63	0,6281	61
Lebanon	0,5931	65	0,5964	65	**0,5997**	**67**	0,6031	70	0,6064	70
Liberia	0,4290	96	0,4412	96	**0,4535**	**97**	0,4657	97	0,4780	96
Lithuania	0,6260	51	0,6369	48	**0,6479**	**48**	0,6589	47	0,6699	46
Madagascar	0,4295	95	0,4430	95	**0,4565**	**96**	0,4699	95	0,4834	95
Malaysia	0,7722	21	0,7727	22	**0,7732**	**22**	0,7737	23	0,7743	24
Malta	0,6431	43	0,6458	45	**0,6485**	**47**	0,6513	48	0,6540	48
Mauritania	0,4147	98	0,4269	99	**0,4390**	**99**	0,4512	98	0,4634	98
Mauritius	0,6043	59	0,6102	59	**0,6162**	**59**	0,6222	59	0,6281	60
Mexico	0,6749	37	0,6784	39	**0,6818**	**41**	0,6853	41	0,6888	42
Moldova	0,4027	100	0,4329	98	**0,4630**	**94**	0,4931	94	0,5232	92
Montenegro	0,4889	88	0,5083	86	**0,5278**	**83**	0,5472	80	0,5667	78
Morocco	0,6299	49	0,6314	52	**0,6328**	**51**	0,6343	52	0,6357	54
Netherlands	0,8403	12	0,8439	12	**0,8475**	**12**	0,8510	13	0,8546	12
New Zealand	0,7458	24	0,7570	24	**0,7683**	**23**	0,7796	22	0,7908	22
Nigeria	0,5062	81	0,5123	85	**0,5184**	**87**	0,5245	89	0,5306	90
Norway	0,6661	41	0,6864	36	**0,7068**	**35**	0,7271	29	0,7475	25
Oman	0,7183	29	0,7208	29	**0,7234**	**29**	0,7259	30	0,7284	31
Pakistan	0,5272	75	0,5299	76	**0,5326**	**78**	0,5354	84	0,5381	86
Panama	0,7118	30	0,7154	30	**0,7190**	**30**	0,7226	32	0,7262	32
Paraguay	0,4761	91	0,5016	89	**0,5272**	**84**	0,5527	77	0,5782	73
Peru	0,5976	62	0,6015	63	**0,6054**	**64**	0,6094	65	0,6133	67
Philippines	0,5880	66	0,5952	66	**0,6023**	**66**	0,6094	66	0,6165	66
Poland	0,7222	26	0,7275	26	**0,7328**	**27**	0,7381	27	0,7434	27
Portugal	0,7799	19	0,7840	21	**0,7880**	**21**	0,7920	21	0,7961	21
Qatar	0,7546	23	0,7609	23	**0,7672**	**24**	0,7735	24	0,7798	23
Romania	0,5973	63	0,6068	61	**0,6163**	**58**	0,6257	58	0,6352	55
Russian Federation	0,6149	55	0,6195	55	**0,6241**	**55**	0,6287	56	0,6334	59
Saudi Arabia	0,7012	34	0,7026	34	**0,7040**	**36**	0,7054	36	0,7067	37
Senegal	0,4810	89	0,4882	92	**0,4953**	**92**	0,5024	92	0,5095	94
Sierra Leone	0,4042	99	0,4150	101	**0,4258**	**101**	0,4366	101	0,4474	101
Singapore	0,9450	1	0,9459	1	**0,9468**	**1**	0,9477	1	0,9486	1
Slovenia	0,6687	39	0,6762	40	**0,6838**	**38**	0,6913	37	0,6989	38
South Africa	0,7191	28	0,7247	28	**0,7302**	**28**	0,7358	28	0,7413	30
Spain	0,8886	7	0,8903	8	**0,8920**	**8**	0,8936	8	0,8953	9
Sri Lanka	0,6080	57	0,6086	60	**0,6092**	**62**	0,6098	64	0,6104	68
Sweden	0,8324	13	0,8395	13	**0,8466**	**13**	0,8537	11	0,8609	11

Countries	λ = 0,00		λ = 0,25		λ = 0,50		λ = 0,75		λ = 1,00	
	Score	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
Taiwan, China	0,8132	16	0,8146	16	**0,8160**	**17**	0,8174	18	0,8188	18
Thailand	0,7329	25	0,7355	25	**0,7381**	**25**	0,7406	26	0,7432	28
Trinidad and Tobago	0,4937	87	0,5020	88	**0,5103**	**90**	0,5185	90	0,5268	91
Tunisia	0,5085	80	0,5249	78	**0,5413**	**76**	0,5577	76	0,5741	76
Turkey	0,7041	32	0,7063	33	**0,7084**	**32**	0,7106	34	0,7128	34
Ukraine	0,6005	61	0,6064	62	**0,6122**	**61**	0,6180	62	0,6238	63
United Arab Emirates	0,8880	8	0,8909	7	**0,8938**	**7**	0,8968	7	0,8997	7
United Kingdom	0,8979	6	0,8997	6	**0,9015**	**5**	0,9033	5	0,9050	5
United States	0,8987	5	0,8999	5	**0,9012**	**6**	0,9024	6	0,9037	6
Uruguay	0,6058	58	0,6107	58	**0,6157**	**60**	0,6206	61	0,6255	62
Venezuela, RB	0,4372	94	0,4469	94	**0,4565**	**95**	0,4662	96	0,4758	97
Vietnam	0,7047	31	0,7063	32	**0,7079**	**34**	0,7095	35	0,7112	35

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ORIGINAL PAPER

THE APPLICATION OF ADABOOST.M1 BASED ON ANT COLONY OPTIMIZATION TO CLASSIFY THE RISK OF DELAY IN THE PHARMACEUTICAL SUPPLY CHAIN

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ABSTRACT. Background: The purpose of this article is to present the developed AdaBoost.M1 based on Ant Colony Optimization (hereby referred to as ACOBoost.M1 throughout the study) to classify the risk of delay in the pharmaceutical supply chain. This study investigates one research hypothesis, namely, that the ACOBoost.M1 can be used to predict the risk of delay in the supply chain and is characterized by a high prediction performance.

Methods: We developed a machine learning algorithm based on Ant Colony Optimization (ACO). The meta-heuristic algorithm ACO is used to find the best hyperparameters for AdaBoost.M1 to classify the risk of delay in the pharmaceutical supply chain. The study used a dataset from 4PL logistics service provider.

Results: The results indicate that ACOBoost.M1 may predict the risk of delay in the supply chain and is characterized by a high prediction performance.

Conclusions: The present findings highlight the significance of applying machine learning algorithms, such as the AdaBoost.M1 model with Ant Colony Optimization for hyperparameter tuning, to manage the risk of delays in the pharmaceutical supply chain. These findings not only showcase the potential for machine learning in enhancing supply chain efficiency and robustness but also set the stage for future research. Further exploration could include investigating other optimization techniques, machine learning models, and their applications across various industries and sectors.

Keywords: Ant Colony Optimization, AdaBoost.M1, Machine Learning, Supply Chain Risk management, Delay prediction

INTRODUCTION

In the modern era, the advancement of information and communication technology (ICT) has become critically important for enterprises. Technological progress has given rise to novel tools that facilitate more efficacious support for organizations in their operations. One of the most prominent trends in recent years is the escalating interest in artificial intelligence (AI) and its implementation in the business domain.

One of the principal fields of inquiry within the domain of artificial intelligence is that of machine learning [Hastiem Tibshirani, & Friedman, 2009; Mitchell, 1997; Russel & Norvig, 2021]. The most common task in machine learning is classification [Kozak, 2019], which assigns any description of an object's decision from a finite set of decisions. For example, there may be a need to classify certain deliveries by assigning them a decision of whether there is a risk of delay or not. A particular subtask of classification is called supervised learning. In this subtask, a finite set of objects (also called instances or cases) is provided, each with known decisions assigned to them. This set is called the training set; in the example considered here, it is the set of deliveries in the supply chain with assigned information about the risk of delay. The goal is to assign appropriate decisions (e.g., risk of delay or not) to new objects called test objects (e.g., new deliveries to be examined). One example of

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supervised learning is the AdaBoost.M1 algorithm[1].

The learning algorithm itself has parameters called hyperparameters. These parameters refer to the settings or configurations of the methods that can be freely selected within a certain range and have an impact on the performance or quality of the model [Bartz, Bartz-Beielstein, Zaefferer, & Mersmann, 2023]. Selecting hyperparameters manually is time-consuming, repetitive, and requires ad-hoc decisions by the practitioner [Hatıpoğlu, Tosun, & Tosun, 2022]. Metaheuristic methods, such as Ant Colony Optimization (ACO), are among the approaches used to search for optimal hyperparameters. Fig 1. presents an illustration of the problem of utilizing machine learning and ACO for the purpose of hyperparameter optimization.

One industry that can benefit from the potential of machine learning, for example, for supply chain risk management, which aims to protect supply chains from disruption (by predicting the presence of risk factors and mitigating their negative effects) [Wyrembek, 2023] is logistics. From the perspective of 4PL logistics services providers who are responsible for designing, planning, and optimizing the supply chain [Werner-Lewandowska Koliński, & Golinska-Dawson, 2023], it would be significant to predict delays with high prediction performance. It is even more important to predict delays in the pharmaceutical supply chain[2], which has an impact on patient care.

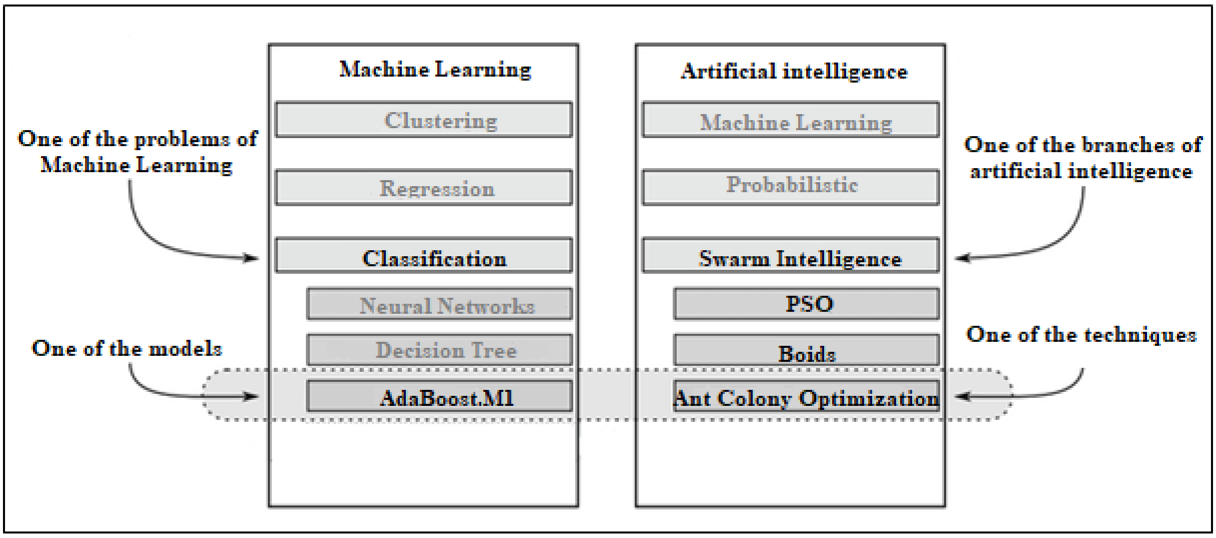

Fig. 1 Problem positioning *Source: Own work based on [Kozak, 2019]*

The aim of this study is to present the developed AdaBoost.M1 based on Ant Colony Optimization (hereby referred to as ACOBoost.M1 throughout the study) to classify the risk of delay in the pharmaceutical supply chain. Furthermore, the research hypothesis has been stated as follows:

[H1] ACOBoost.M1 makes it possible to predict the risk of delay in the supply chain and is characterized by a high prediction performance.

The research hypothesis is justified by works [Baryannis, Dani, & Antoniou, 2019; Trajkovski, & Madjarov, 2022], in which Baryannis et al. [2019] train classifiers to determine whether a delivery is late or not. Following Trajkovski & Madjarov's study [2022] it was demonstrated that optimizing hyperparameters of machine learning models using ACO resulted in high predictive performance.

[1] The terms “algorithm”, “model”, and “method” will be used interchangeably in this work

[2] The term „Pharmaceutical Supply Chain” is defined in this work as the supply chain of drug.

Literature Review on Machine Learning and predicting delays in the supply chains

Machine learning and supply chains delay started to be studied not long ago. This is the reason for the scarcity of publications on this topic, indicating an existing research gap that remains open. In the body of literature regarding late deliveries in the supply chain, studies by [Baryannis et al., 2019; Biazon de Oliveira et al., 2021; Steinberg, Burggräf, Wagner, & Heinbach, 2022; Wyrembek, 2022; Steinberg et al., 2023] have been found.

First, Baryannis et al. [2019] and Wyrembek [2022] face difficulties in handling data with high dimensionality, which is commonly referred to as the curse of dimensionality. If these machine learning projects were implemented in business operations, they would likely be deemed unsuccessful from a practical standpoint. Baryannis et al. [2019] compare three models: Support Vector Machine, Unrestricted Decision Trees, and Restricted Decision Trees. The best model was SVM with an accuracy of 94%. When it comes to Wyrembek [2022], Logistic Regression was used with AUC on the level 0,96. In these works [Biazon de Oliveira et al., 2021; Steinberg et al., 2022; Steinberg et al., 2023], regression was used instead of classification. Biazon de Oliveira et al. [2021] compare five models: Linear Regression, Linear Support Vector Machine, Random Forest, K-Nearest Neighbors, and Multi-Layer Perceptron. The best algorithm to forecast the lead time was SVM. They focused only on analyzing a selected link, rather than the entire pharmaceutical supply chain. The studies [Steinberg et al., 2022; Steinberg et al., 2023] are conducted only on one application case and may not be representative for other industries.

METHODOLOGY

In this section, the proposed approach is introduced.

Adaboost.M1 as an example of Boosting

Boosting is a machine learning technique that involves constructing multiple weak classifiers using pseudo-samples and employing them for classification through voting. The probability distribution of selecting elements from the learning set is not uniform but depends on the classification errors of the individual classifiers in the ensemble. Each element in the learning set is assigned a weight that determines its probability of being chosen for the pseudo-samples. After generating a pseudo-sample, a classifier is built and evaluated, and the weights of incorrectly classified elements are increased to raise their likelihood of being selected for subsequent pseudo-samples. This process is repeated for each classifier in the ensemble, leading to a balanced set of classifiers with greater accuracy than a single classifier [Kozak, 2019]. AdaBoost.M1 (the method was invented in 1995 by Freund and Schapire [Chengsheng, Huacheng, & Bing, 2017]) is a particular type of boosting that modifies the weights of objects in the learning set based on the classification errors of the individual classifiers already in the ensemble [Wyrembek, 2023]. Weight modification is dependent on the total weight of wrongly classified objects [Kozak, 2019]:

$$\varepsilon(j) = \sum_{x_i} \quad we_i\left[c_i \neq c_i^j\right] \quad [1]$$

where we_i is the weight of object x_i, and c_i^j is the decision class of the analyzed object.

If the classification error is less than or equal to 0.5, the weights are modified accordingly. Otherwise, the weights are multiplied by a coefficient [2] and then normalized [Kozak, 2019].

$$\kappa(j) = \frac{1-\varepsilon(j)}{\varepsilon(j)} \qquad [2]$$

In the case of boosting, there is voting with weights, in which a single classifier gets the weight [Kozak, 2019][3]:

$$dDF(x) \coloneqq \underset{y \in Y}{argmax} \sum_{j=1}^{J} \left(log\frac{1}{\kappa_j}\right) h_j(x,y).$$

The pseudocode of AdaBoost.M1 is presented in Fig. 2. Example hyperparameters of AdaBoost include the learning rate and n_estimators [Gao, & Liu, 2020].

Algorithm 1: The AdaBoost.M1 algorithm

```
weight_of_objects[1..n] ← 1/n;
ensemble ← NULL;
weight_of_objects ← NULL;
for number_of_classifiers do
    {Construction of the classifier with a weighted vote}
    data_set_classifier ← choose_objects(data_set, weight_of_objects);
    new_classifier ← build_classifier(data_set_classifier);
    new_classifier.determine_the_weight_of_voting();
    ensemble.add(new_classifier);
    {Calculate the new weight of objects}
    for number_of_objects do
        κ ← classifies_object(current_object, ensemble) {by Eq. [2]}
        weight_of_objects[current_object] ← weigh_of_objects[current_object] · κ
    end for
end for
result ← ensemble
```

Fig. 2. The pseudocode of AdaBoost.M1 algorithm *Source: Own work based on [Kozak, 2019]*

Ant Colony Optimization

The Ant Colony Optimization algorithm (ACO) was first presented in the early 1990s in relation to combinatorial optimization problems, particularly the traveling salesman problem and job shop scheduling [Colorni, Dorigo, & Maniezzo, 1991; Colorni, Dorigo, Maniezzo, & Trubian, 1994] and is a form of artificial intelligence called swarm intelligence [Boryczka & Kozak, 2010].

Their idea is based on observing the behavior of ants in the ecosystem [Boryczka & Kozak, 2016]. Research by Dorigo in his PhD Thesis has shown that ants have limited abilities when acting individually, but their efficiency greatly increases when they act as a group [Socha, & Blum, 2006]. In the experiment, the behavior of ants during their search for food and where they left pheromones on their path was observed, and subsequent ants followed the amount of pheromones on each path. Shorter paths were found to be more preferred as more ants could pass through them in a unit of time, leaving more pheromones on them. However, the entire process was not fully determined as ants could choose a different path despite the presence of pheromones on a given path [Jadczak, 2019]. Figure 3 presents the pseudocode of the ACO metaheuristics algorithm.

Algorithm 2: Ant Colony Optimization

```
procedure ANT_COLONY_OPTIMIZATION
    initialization()
    while (termination_conditions_not_met) do
        construct_ant_solutions()
        apply_local_search()                    ▷ Optional
        update_pheromones()
    end while
end procedure
```

Fig. 3. The pseudocode of ACO metaheuristics algorithm *Source: Own work based on [Kozak, 2019]*

One iteration of the loop involves all ants constructing solutions, optionally improving them using a local search algorithm, and updating the pheromone levels. The subsequent sections provide a more detailed explanation of the algorithm [Kozak, 2019]:

- **initialization() -** At the beginning of the algorithm, the approach parameters are set and all pheromone variables are initialized to a value τ0, which is a parameter of this algorithm [Kozak, 2019; Jadczak, 2019].
- **construct_ant_solution() -** The choice of a solution is made probabilistically in each step of construction. The node transition rule is modified to explicitly allow for exploration. An ant *k* positioned at an analyzed node *i* chooses node *j* to move to and thus follows the rule [Boryczka & Kozak, 2010; Kozak, 2019; Jadczak 2019][4]:

$$j = \begin{cases} argmax_{u \in J_i^k} \{[\tau_{iu}(t)] \cdot [\eta_{iu}]^{\beta}\} & if q \leq q_0 \\ J & if q > q_0 \end{cases},$$

where the pheromone amount τiu(t) currently present on the edge (*i*, *u*) at time *t* is multiplied by the heuristic value ηiu between nodes *i* and *u*. A random variable *q*, which is uniformly distributed between 0 and 1, is used to determine the probability of a certain node being selected as the next node to be traversed. The parameter q_0, which can be adjusted, is used to control the balance between exploration and exploitation. Finally, $J \in J^k_i$ represents the node being analyzed, and it is chosen randomly with a probability determined by:

$$p_{iJ}^k(t) = \frac{\tau_{iJ}(t) \cdot [\eta_{iJ}]^{\beta}}{\sum_{l \in J_i^k} [\tau_{il}(t)] \cdot [\eta_{il}]^{\beta}} \qquad [5]$$

- **apply_local_search() - optional -** After the construction of solutions, further steps may be needed before updating the pheromones, which are often referred to as daemon actions [Kozak & Boryczka, 2016]. One common daemon action is to apply local search to the solutions, using the locally optimized solutions to determine which pheromone values to update in the matrix [Socha, & Blum, 2006].
- **update_pheromones() -** The goal of updating pheromones is to enhance pheromone values linked with good or potentially good solutions while reducing ("punishing") those related to bad solutions. Typically, this is accomplished by decreasing all pheromone values through pheromone evaporation and increasing the pheromone levels of selected good solutions [Kozak, 2019]. Pheromone evaporation is needed to avoid a too rapid convergence of the algorithm [Boryczka & Kozak, 2016].

ACOBoost.M1

The ACO method, in conjunction with the AdaBoost.M1 model, serves to optimize the hyperparameters of the classification model. In the context of hyperparameter optimization, ants traverse the hyperparameter space in order to find the best set of parameters for the boosting model.

In the algorithm, each ant represents a potential set of hyperparameters. The ants explore the hyperparameter space, taking into account the attractiveness of individual values. Attractiveness is calculated based on pheromones and cross-validation error. Pheromones are updated in each iteration, allowing for dynamic exploration of the hyperparameter space.

The ACO algorithm is executed for a specified number of iterations, and in each iteration, ants traverse the hyperparameter space, evaluate the cross-validation error, and update the pheromones. Based on the pheromones and attractiveness, ants select the subsequent hyperparameter values, leading to the ultimate optimal set of hyperparameters.

In this particular task, the AdaBoost.M1 model is optimized with regard to two hyperparameters: the number of estimators ('n_estimators') and the learning rate ('learning_rate'). The ACO algorithm searches the hyperparameter space to find the best values for these parameters, which result in the lowest cross-validation error.

Upon completion of the ACO algorithm and identification of the best hyperparameters, the AdaBoost.M1 model is trained on the training data set using these optimal parameters. As a result, we obtain a model with higher accuracy and improved generalization ability on novel data. Fig. 4 presents the pseudocode of the ACOBoost.M1 algorithm.

Algorithm 3: ACOBoost.M1 Algorithm

```
initialize best_hyperparameters;
set_ACO_parameters;
set best_error := infinity
set best_parameters := null
for i = 1 to max_iterations do
    for j = 1 to num_hyperparameters do
        for a = 1 to num_ants do
            generate_parameters_list
        end for
    end for
    for j = 1 to num_hyperparameters do
        for a = 1 to num_ants do
            calculate_error
            if current_error < best_error then
                best_error := current_error
                best_parameters := current_parameters
            end if
        end for
        calculate_attractiveness
    end for
    for j = 1 to num_hyperparameters do
        for a = 1 to num_ants do
            update_pheromone_trail
        end for
    end for
end for
return best_parameters
train_AdaBoost_model(ACO_best_parameters, X_train, y_train)
predict_and_evaluate(X_test, y_test)
if new_classifier_performance > best_classifier_performance then
    best_classifier := new_classifier
end if
report_performance_metrics
```

Fig. 4. The pseudocode of ACOBoost.M1 algorithm

CASE STUDY

For this case study, we chose a 4PL logistics services provider that designed and manages a pharmaceutical supply chain. To develop a model, we applied the established CRISP-DM procedure model (presented in Fig. 5) [Sarkar, Bali, & Sharma, 2018]. As a result, this section will proceed according to the phases of CRISP-DM, including business understanding, data understanding, data preparation, modeling, evaluation, and deployment. As we primarily focused on model development, we excluded the last phase, namely, Deployment. The case study was carried out on a computer with an 8-core CPU, 8-core GPU, and 8 GB RAM.

Business Understanding

The Business understanding phase typically includes a description of the business problem and a transfer of the business problem into concrete requirements and objectives for further data analysis [Steinberg et al., 2023].

As the business problem is delays in pharmaceutical supply chains, our goal is to classify whether a delivery is delayed or not using ACOBoost.M1. We assume that the risk of delay is real and has been classified into binary categories, where 0 indicates on-time delivery and 1 indicates delayed delivery.

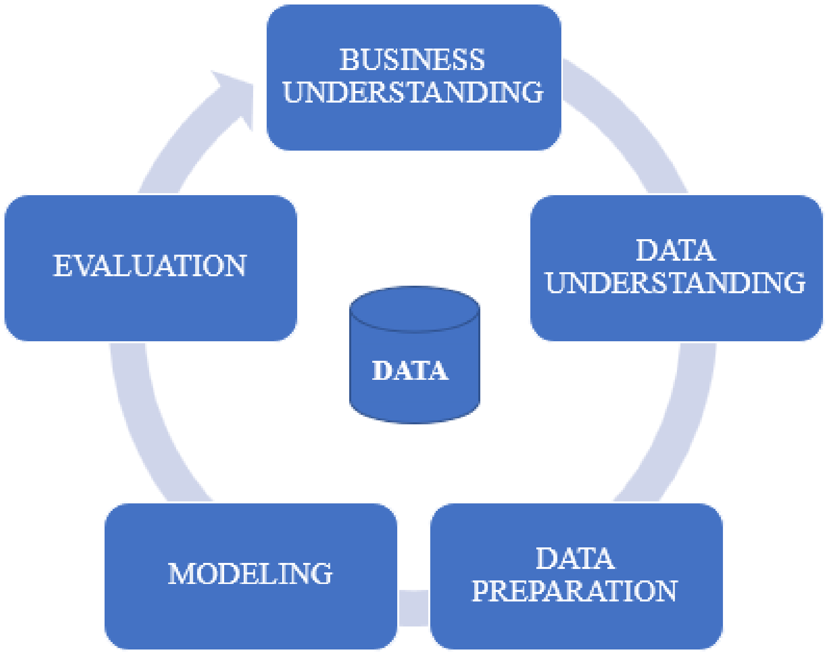

Fig. 5 CRISP-DM model *Source: Own work based on [Sarkar, Bali, & Sharma, 2018]*

Data Understanding

The dataset contains 6711 instances, where a single instance represents a delayed delivery in the supply chain. Each instance is described by eleven input attributes described in Table 1. The target variable is **Risk**.

The data was collected in the first quarter of 2023. As shown in Figure 6, we can observe that 17.1% of deliveries were delayed and 82.9% were on time. In the dataset, there are 1847 missing values for the **Month** and **Kilometers** categories, respectively. Figure 7 presents a missingness map, which shows where the missing values occurred exactly.

Table 1. Attributes

Attribute	Description	Type
Supplier	ID of the Supplier	Object
Month	Month of delivery	Float64
Kilometers	Kilometers to place of delivery	Float64
ID_ODB_T	Binary recipient category - 0 represents pharmacy, 1 represents hospital pharmacy.	int64
Weight	Weight of the parcel	Float64
Freight	Cost of delivery	Float64
Parcel	Number of packages in the delivery	int64
Type of delivery	Type of delivery. Classic - delivery within 72 hours, premium – delivery within 24 hours	Object
Status	Status of the delivery	Object
Country	Country of the delivery	Object
Carrier	Carrier that delivered the parcel	Object
Risk	Binary category – 0 – represents on time delivery, 1, represents delayed delivery	int64

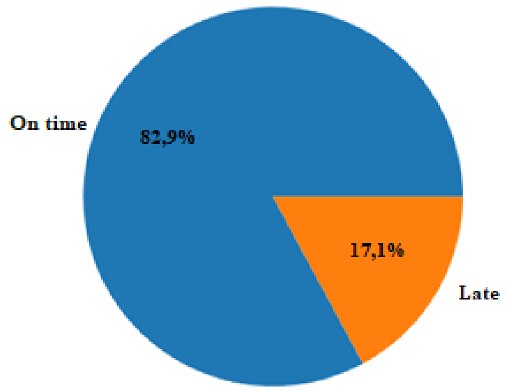

Fig. 6. On-time and delayed deliveries as a percentage.

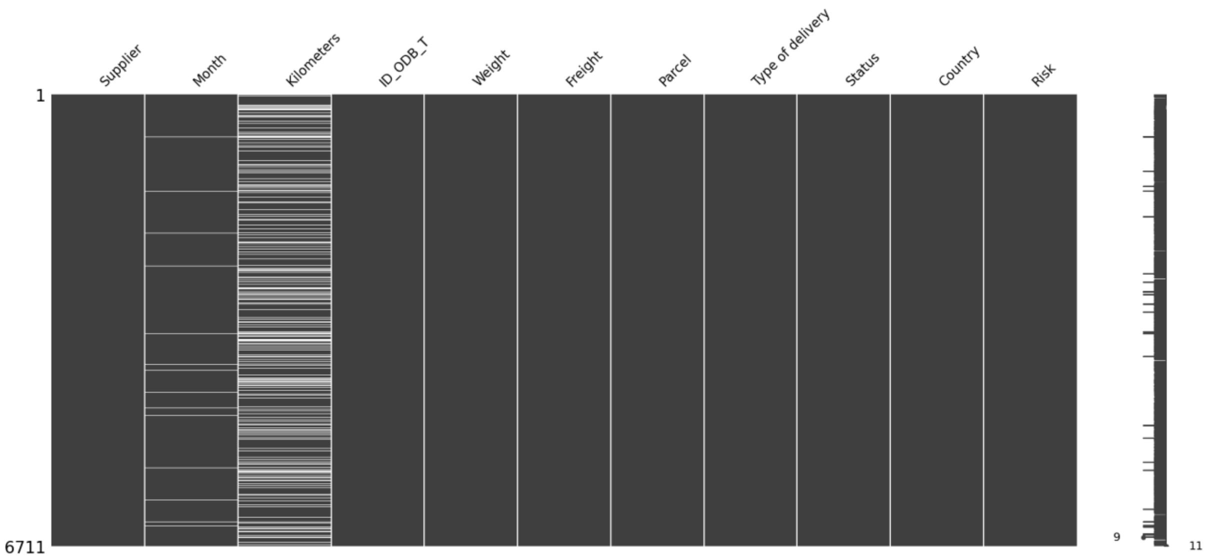

Fig. 7. Missingness map

Data Preparation

Based on the knowledge and insight acquired from the dataset, a standard pre-processing phase was applied, including cleaning and removal of duplicates and corrupted data, outlier detection, manipulation of missing values, correlation analysis, Cramér's V, and Pearson correlation coefficient [Ristoski, & Paulheim, 2016; Kuhn, & Johnson, 2016].

As we did not find any duplicates in our dataset, we handled missing values. As was shown in the previous section, there are 1847 missing values for the **Month** and **Kilometers** categories. Following Emmanuel et al. [2021], we use a simple imputation method such as a mean to fill the missing values. After removing outliers and using correlation analysis, Cramér's V, and Pearson correlation coefficient, we chose the following variables: **Month**, **Kilometers**, **ID_ODB_T**, **Weight, Parcel**, **Type of delivery**, **Country**, **Carrier**, and **Risk**. The next step was to make a dummy variable from the **Carrier**, **Type of delivery,** and **Country** categories. The final step of the pre-proccesing was data normalization [Dong, & Liu, 2018].

Modeling

After understanding the data and defining the features of our ACOBoost.M1 model, we train it. To train a model we use the Python programming language utilizing the scikit-learn, numpy, pandas, and random libraries.

Firstly, we set up Ant Colony Optimization parameters. The ACO algorithm parameters used in our study include the number of ants set to 100, the number of iterations set to 50, and the evaporation coefficient set at 0.7. The algorithm searched for the best hyperparameters for 23 hours, 25 minutes, and 10 seconds. Upon completion of the optimization process, the best hyperparameters for the ACOBoost.M1 model were identified as ('n_estimators': 54, 'learning_rate': 1.0).

Figure 8 represents a pheromone map created when ACO finished running. The pheromone map displays the quantity of pheromones for each combination of hyperparameters (in this case, 'n_estimators' and 'learning_rate') and ants. Each column represents an ant, while each row corresponds to a hyperparameter. The values in the pheromone map indicate the attractiveness of a given hyperparameter for the ants. The greater the pheromone value, the higher the likelihood that an ant will select that particular hyperparameter. The ACO algorithm relies on an iterative process in which ants update the pheromone map based on the quality of the solutions they have found. As a result, higher pheromone values indicate better solutions. [Kozak, & Boryczka, 2016; Kozak, 2019]. The map provides an insight into the collective exploration and search behavior of the ants as they traverse the hyperparameter space in pursuit of optimal solutions for the ACOBoost.M1 model.

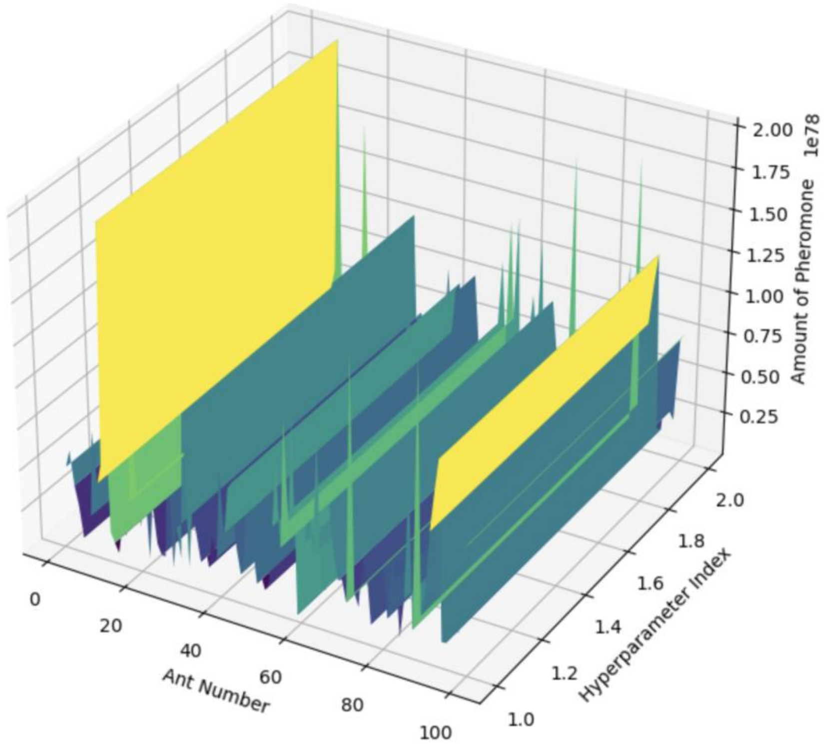

Fig. 8. Pheromone map created when ACO finished running

In the pheromone map shown in Figure 8, it can be observed that the pheromone values differ between ants but are generally quite high. These values signify the appeal of hyperparameter combinations for the ants. We can deduce from this that the ACO algorithm has identified certain hyperparameter combinations as more attractive than others. Attention should be paid to the hyperparameter combinations with the highest pheromone values. These values suggest that a given hyperparameter combination yielded better results during the optimization process.

Evalutation

In the context of binary classification problems, such as the one under consideration, instances can be labeled as either positive or negative. Taking this dichotomy into account, the classification outcomes can be organized into four distinct categories, which create the confusion matrix: true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN). Both TP and TN represent instances where the classification has been performed correctly. FP is a false alarm, also called a Type I error, and FN represents miss-classified ones, also called a Type II error [Hatıpoğlu, 2022; Wyrembek, 2023].

Derived from the confusion matrix, several performance measures can be computed for the model, encompassing [Iwendi et al, 2022; Wyrembek, 2023]:

- Accuracy - the proportion of correctly classified instances among the total number of instances, which includes true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN).
- Precision - a metric reflecting the model's effectiveness, signifying the ratio of true positives (TP) to the combined count of true positives (TP) and false positives (FP).
- Recall - the ratio of true positives (TP) to the sum of true positives (TP) and false negatives (FN), indicating the model's ability to identify positive instances correctly.
- F1 Score - this measure represents the harmonic mean of precision and recall, offering a balanced perspective on the model's performance.

Table 2 contains a summary of performance metrics and classification. The confusion matrix reveals that the model successfully identified 1129 instances with a risk of delay (TP) and 30 instances without a risk of delay (TN). However, it also misclassified 181 instances with a risk of delay (FP) and 3 instances without a risk of delay (FN).

Table 2 Summary of Performance measures and classification

Performance measures				**Classification**			
Accuracy	Precision	Recall	F1 Score	TP	FN	FP	TN
0.862	0.861	0.997	0.924	1129	3	181	30

The model's accuracy of approximately 86.3% demonstrates its ability to correctly classify instances in the majority of cases. With an F1 score of roughly 0.924, the model demonstrates a robust equilibrium between recall and precision in detecting instances involving a risk of delay. The high recall of approximately 99.7% indicates that the model is adept at identifying instances with a risk of delay, as it manages to capture nearly all of the actual positive instances. A precision of approximately 86.2% signifies that 86.2% of the instances predicted as having a risk of delay by the model are indeed at risk of delay.

DISCUSSION

Based on the results obtained, it can be concluded that the ACOBoost.M1 model effectively predicts the risk of delay in the pharmaceutical supply chain, thereby supporting Hypothesis H1. The model's high predictive performance, with an accuracy of about 86.3%, substantially exceeds the levels of accuracy forecasted in the study by Baryannis et al. [2019]. This suggests that ACOBoost.M1 might outperform traditional classification models such as SVM in predicting delay risk.

Our findings confirm and extend those of Trajkovski and Madjarov [2022], who demonstrated that hyperparameter optimization of machine learning models using ACO resulted in high predictive performance. The model's F1 score of approximately 0.924 indicates a strong balance between recall and precision. These results, coupled with a high recall of nearly 99.7% and a precision of about 86.2%, demonstrate that the ACOBoost.M1 model is effective at identifying and predicting instances with a risk of delay.

However, our study, like others [Baryannis et al., 2019; Biazon de Oliveira et al., 2021; Steinberg et al., 2023; Wyrembek, 2022], has certain limitations. Our results are based on a specific dataset, and the model's performance may vary when applied to different datasets or contexts.

Future research should focus on applying the ACOBoost.M1 model to different datasets and contexts to assess its versatility and potential for improvement. In line with the results of previous studies, our results provide strong evidence that the ACOBoost.M1 model is a powerful tool for predicting the risk of delay in the pharmaceutical supply chain.

CONCLUSION

In today's world, the importance of applying machine learning is continually growing and can be utilized across numerous industries, potentially in all of them. For instance, the medical industry can leverage these algorithms to manage risk in the supply chain to protect against disruptions (by predicting the occurrence of risk factors).

In this article, we presented a different approach to the classification problem in machine learning. The Ant Colony Optimization algorithm was employed for hyperparameter tuning to construct an AdaBoost.M1 model, which classifies the risk of delay in the pharmaceutical supply chain.

The ACOBoost.M1 model has demonstrated its effectiveness in managing the risk of delay in the pharmaceutical supply chain. Its high prediction performance, as evidenced by its accuracy, F1 score, recall, and precision, indicates that the model can reliably identify instances with a risk of delay. This ability is crucial for decision-makers in the pharmaceutical industry to implement timely mitigation strategies and maintain supply chain efficiency.

In light of these findings, the ACOBoost.M1 model can serve as a valuable tool for organizations operating in the pharmaceutical supply chain. By incorporating this model into their risk management strategies, companies can proactively address potential delays, optimize their logistics processes, and ultimately improve overall supply chain performance. Future research and model refinement, including further exploration of hyperparameters, will help enhance the model's predictive capabilities and its applicability to various pharmaceutical supply chain scenarios.

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ORIGINAL PAPER

THE IMPACT OF SUPPLIER STRATEGIC PARTNERSHIP IN SUPPLY CHAIN ON ORGANIZATIONAL PERFORMANCE: AN EMPIRICAL STUDY OF SUPPLY CHAIN MANAGEMENT IN AN EMERGING ECONOMY

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ABSTRACT. **Background**: The purpose of this study is to create a theoretical framework for analyzing the causal relationship between supply chain management practices and firm performance, in the FMCG sector of Pakistan. A quantitative research approach was adopted, in which a multi-item scale Web-based survey using a structured online questionnaire was utilized to collect the primary data. A total of 232 questionnaires were collected from a sample of Karachi-based FMCG companies in Pakistan. Confirmatory Factor analysis and internal consistency were used to test the reliability and fitness of the measurement model, and structural equation modeling-SEM was employed to test the proposed hypotheses. Empirical findings reveal that there is a significant positive relationship between SCM practices and firm performance. However, the results of the individual-level analysis of SCM practices appear to vary from practice to practice. Of various SCM practices, supplier strategic partnership SSC with the highest beta value (i.e., ß = 0.488; t-value = 32.381; p _ 0.000) was found to have the greatest impact on firm performance, followed by information sharing customer relationship, and finally the outsourcing. This study will guide supervisors with a more in-depth understanding of SCM practices and their potential contribution to firm performance. The findings also encourage managers to place supplier strategic partnerships and information systems on high priority, on both inter-firm and intra-firm relationships, as prerequisites for achieving superior firm performance. The propositions and results of the study provide managers with guidelines about effective management of upstream supply chain networks and awareness of the potential synergies that arise from suppliers and the information system. This article further enriches the literature in an evolving area of supply chain management practices. Two key factors facing supply chain managers and scholars are addressed, and establish their ability to drive firm performance.

Keywords: Supply chain management (SCM) practices, Supplier strategic partnership, customer relationship, Information system, outsourcing, organization performance

INTRODUCTION

The present business environment is highly competitive, vibrant, and globalized. Therefore, to survive in this challenging arena, organizations are moving toward implementing various supply chain strategies such as supply chain integration, customer relationship management, outsourcing, etc. It is because better practices in the supply chain stimulate responsiveness in the supply chain and help organizations gain a better competitive advantage (Abdul-Hamid et al., 2020). However, companies are connecting their supply chain partners by integrating them and also connecting their internal operations, because internal operations act as mediators between SCM practice and firm performance (Doan, 2020). Furthermore, in the previous decade, the key rationales behind market competitiveness were to provide great services along with quality products delivered at the required place at the right time on the cheapest way. But now organizations realize that these aspects are not just enough to enhance a firm's capabilities, rather their entire supply chain has to be refocused and made competitive (Niknejad &

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Petrovic, 2016). Therefore, the implementation and adaptation of SCM practices are very essential to remain competitive and survive in this global market and for increasing profitability (Blonska et al., 2013; Flöthmann et al., 2018). Furthermore, several organizations have paid more attention to the supply chain, as it has been observed and realized in the end that they cannot survive in a competitive market without an effective relationship with their customers, as well as a supplier or other entities in the supply chain network (Ghalem et al., 2018). As stated by (Chavez & Seow, 2012; C. S. Tang, 2006) that, recently organizations do not compete separately as independent entities without having an appropriate supply chain. Therefore, organizations realized that an effective supply chain is essential to stay competitive in the local and global markets. This can be possible if a firm adopts and implements various SCM practices, such as the use of updated information and communication systems across the supply chain network and building relationships with the customer and the supplier using the Internet or social media platforms (Basnet et al., 2003; Chand, 2021; Langdon et al., 2021). According to (Betts & Johnston, 2005; Rehman Khan & Yu, 2019), the implementation of SCM practices increases return on investment to the optimized desired level, the organizations are financially benefited from an effective supply chain which also enhances competitiveness. In this regard, SCM practices have played a pivotal role in the effectiveness of any organization because more than an era, it presents its competitive advantage toward this success (Pujawan & Geraldin, 2009). (Choy & Lee, 2002) explained the importance of adopting SCM practices and concluded that effective SCM practices improve the firm's performance and also contribute up to 50% of profitability by cost reduction. In Pakistan, manufacturing companies are lagging in the implementation of SCM practices, so this study deals with this problem and provides frameworks that identify key SCM practices that improve firm performance by identifying their impact. Therefore, the objective of the study is to investigate the different SCM practices implemented in different FMCG companies and to determine their influence on firm performance.

The rest of this paper is structured as follows. Section 2 presents the literature review and hypothesis development, which lay the basis for developing the proposed conceptual framework. In Section 3, the research methodology used in this study is explained along with the support of materials and methods. Section 4 presents the data analysis and results of the proposed theoretical framework using structural equation modeling (SEM) using smart PLS 4, and finally, the discussion and conclusions are given in Section 5, along with the limitations and implications.

LITERATURE REVIEW

Theoretical Background

The main theoretical foundation for developing the proposed framework is derived from the resource-based view (RBV), which conceives a distinctive set of means possessed by organizations that are more likely to clarify variations in firm performance (Barney, 1991) that also incorporate firm competencies. In this research, SCM practices are viewed as the capabilities of the firm to form long-term relations with suppliers, thus establishing strategic partnerships, the ability to share information with key stakeholders, developing strong customer relationships, and outsourcing various firm operations. (Attri et al., 2017; Hussein Zolait et al., 2010) proposed that SCM practices affect firm performance and quality performance. The theory of transactional cost economics TCE (Bendoly & Kaefer, 2004) concerning SCM provides a natural fit because it centers on creating the potential for opportunism and SCM practices provide that opportunity, which when implemented will improve firm performance.

Empirical Studies

Supply Chain Management Practices (SCMP)

In the present era, due to the highly competitive market, organizations are adopting various practices in the supply chain just to improve their performance, which helps them to survive in this competitive market. Several organizations adopt different supply chain practices and some commonly used practices are also mentioned given above in Table 1. SCMP is the set of actions within the firm that enhances the performance of the organization in its supply chain department (Amling & Daugherty, 2020; Koh et al., 2007). An exploratory study conducted by a researcher (Omain, 2017) argued, based on previous research, that the execution of SCMP varies based on the nature of organizations and their country's different management styles, and differences in cultures. This concludes that organizations of different countries have different sets of SCMP, due to the information that various managerial concepts that how SCM elements are related to the organization and itself. For that reason, there is no constant set of SCMPs used in all organizations in different countries. For example (Chow et al., 2008; Lin et al., 2005) tried to form and authorize major instruments to measure various SCMPs. It includes postponement, information sharing, internal lean, supplier strategic partnership with the supplier, quality of information, and relationship with the customer. Similarly, Table 1 shows the dimensions of SCMP discussed in various pieces of literature:

Table 1 SCM Practices Dimensions

Researchers	Dimensions
(Nag & Ferdausy, 2021)	Strategic Supplier Partnership, Customer Relationship, Sharing information at different levels along with Quality aspects and Delays.
(Owiti et al., 2017)	Benchmarking, Employee involvement, supplier integration, outsourcing.
(Niknejad & Petrovic, 2016)	Supplier and customer relationship, Internal Operations, Information sharing.
(Sukati et al., 2011)	Strategic Supplier Partnership, Customer Relationship, and Information Sharing.
(Flynn et al., 2010)	Integration of Suppliers, Internal Integration, Functional Integration, and Integration with Customers.
(Jharkharia & Shankar, 2004)	Buyer-Supplier relationship, Inventory Management, Supply chain integration.

In analyzing and merging the study, four different features of the practices of SCM are chosen: Strategic Supplier Partnership, Customer Relationship, Information Sharing, and Outsourcing to measure practices of SCM in the local aspect. These practices cover the forward/downstream (toward the customer), backward/upstream (supplier strategic partnership) of both sides of the supply chain, and the flow of information between members. So, it covers the SCM practices from a local context to enhance the performance of organizations.

Hypothesis Development

Impact of Supplier Strategic Partnership (SSP) on Firm Performance.

Research conducted by (Nag & Ferdausy, 2021) proposes that all suppliers are not considered strategic or tactical suppliers. Researchers argue that initially suppliers must be observed strategically to decide on suppliers that contribute their expertise, capabilities, and attractive advantages to buying organization (Dey et al., 2015; Yeung et al., 2013). The SSP needs an effective connection stage between the suppliers and the organization. These entities must have the ability and propensity to create long-term linkages while maintaining an effective relationship with service or parts providers that creates value for each supplier's party (Li et al., 2020; Trent & Monczka, 2003). The Strategic Relationship of suppliers is fully explained as a long-term strong link between the organization and its suppliers. SSP encourages organizations to achieve mutual goals by encouraging shared efforts to solve problems and longtime coordination between parties. As these strategic relationships help to encourage mutual benefits between partners and constant contribution in many major strategic regions such as market, technology advancement, and product development (Ali et al., 2017; Amoako-Gyampah et al., 2019). Tactical partnerships with vendors or suppliers enable organizations to perform more effectively with some major supplier parties that are capable to allocate accountability for the achievement of the best results. The effective supplier participation results in cost-effective design choices, helps in assessments of designs, help in the selection of better technologies and components, and also helps in design evaluation. An organization that uses the strategic alliance concept can perform mutually and also reduce inefficient effort and periods (Li et al., 2006). Thus, the given above discussion shows that if an organization develops a strategic partnership with its supplier, then it can improve its performance.

Hypothesis 1 *H1: Strategic supplier partnership is positively related to firm performance.*

Impact of Customer Relationship on Firm Performance.

Organizations now become aware of their customers or clients, as they have a different or unusual economic value to the firm. Therefore, associations concentrate on a customer-centric approach while moving away from Product-centric marketing (Munir et al., 2020). Few organizations take the issue of managing relationships with customers as a priority. Organizations believe in investment in software and technology, while other companies consider CRM programs additionally in increasing sound & creative relationships among customers. In addition, few organizations have established programs to manage customer relationships to a higher level than other organizations. Therefore, it is evident to recognize types of activities and programs that manage the relationship with customers while relating to the performance of companies and their profitability. Organizations must interact with customers or their clients differently while managing relationships with them at each stage (Reinartz et al., 2004). Comprise all collections of practices that are in use to organize the complaints of customers, construct a long-term relationship with consumers & improving their satisfaction level (Gligor et al., 2019; Hsiao et al., 2010). Researchers (Azad & Ahmadi, 2015) believe CRM (customer relationship management) is an essential practice within SCM. Secure relationships with customers permit organizations to distinguish its product from rivals. This also helps to maintain customer faithfulness and severely widen the importance they offer to their consumers. SCMP-like relationships with customers and suppliers are expected to improve or increase a firm's market share and improve the whole competitive position and ROI or Return on Investment (Chowdhury & Quaddus, 2015; Shekhar & Uma Maheswari Devi, 2015). Healthy relationships with supply chain members, including consumers or customers, are required for the booming implementation of supply chain programs (Mbuthia, M. G &Rotich, 2014). Therefore, this study is proposed as follows:

Hypothesis 2 *H2: Customer relationship is positively related to firm performance.*

Impact of Information Sharing on Firm Performance

The sharing of information is one more decisive element for the achievement of the execution of SCM. Misrepresentation of evidence that weakens the overall performance of a company is a major problem in developing economies (Mahmud et al., 2021). The sharing of information has two sides, quality and quantity. These two aspects mutually play an important role in practicing SCM. In previous studies on supply chains, the information sharing has been used as an individualistic construct (Owiti et al., 2017; Shibin et al., 2020). Flawless information sharing between different players in the supply chain needed the support of the information technology (Ye & Wang, 2013). The exchange of information among the supply chain players is the way that the data can be reached to associate firms by equally confirmed exchange of communication. The allocation of resources along with the relevant information among different players in SCM is an essential condition or requirement for an effective alliance (Olorunniwo & Li, 2010). According to some empirical studies, the connection among the supply chain generates the capacity and ability to share and exchange information between the firms or partners.(Kochan & Nowicki, 2018; Prajogo & Olhager, 2012). To achieve higher firm performance, sharing relevant information frequently and openly will conclude the level of sharing which happens ((Fawcett et al., 2007). (Flynn et al., 2010) recommended that the performance of an organization be distinguished based on the use of information. The criteria for using information make a difference in the performance or profitability of the firms (Zhou & Benton, 2007). The literature discussed above illustrates the positive association between information sharing and firm performance.

Hypothesis 3 *H3: Information sharing is positively related to firm performance.*

Impact of Outsourcing on firm performance

Today, outsourcing the organization's functions of the organization has become an essential mechanism to become aware of the firm's goals and objectives. It is because outsourcing lessens capital investment in convinces, information technology, equipment, and manpower. Outsourcing makes firms flexible in adapting to changes in the marketplace and approaching the important edge of technology (C. H. Tang & Wang, 2021). The organization only requires to contract for the essential level of service to fulfill the latest demand of the customer. When demand flows away from the potential of a firm to fulfill, the concept of outsourcing or a third party helps the firm to fulfill that demand (Bradley, 1994; Yang et al., 2016). (Ma & Wong, 2018) explained that third-party logistics, contract logistics, and outsourcing generally mean a similar thing. However, it must be noticed that outsourcing or third-party logistics may be limited to providing a particular type of service like warehousing (Dekker et al., 2009; Lieb & Bentz, 2004). It is important to emphasize that, like a consistent supplier of parts and materials, contracted logisticians should always provide a high level of services to maintain the level of customer satisfaction, which is how they can keep their clients as strong competitors ((Bustinza et al., 2010; Kenyon et al., 2016). So, the outsourcing of any noncore function significantly increases the firm performance financial as well as nonfinancial (i.e., productivity) (Hsiao et al., 2010). The effect of the relationship between logistic outsourcing and customer services on the competitiveness of organizations states that they hold their functions carefully to achieve their potential goals in the form of competitive advantage (Hsiao et al., 2010; D. Kumar et al., 2010; Rajaguru & Matanda, 2019). The rising popularity and fame of JIT or the just-in-time concept is another main factor of outsourcing promotion. By shifting to just-in-time delivery, control of logistics and inventory has become more critical to operations distributions and manufacturing (Green et al., 2019). The cost of operation in a just-in-time concept environment prompts most of its possible adopters to increase their expertise and resources by using outside sources from their firm structure. Therefore, this study is proposed as follows:

Hypothesis 4 *H4: Outsourcing is positively related to firm performance*

Theoretical Framework

The extended literature review reveals that various supply chain scholars have different views on SCMP and their impact on firm performance. However, the common SCMPs were outsourcing, information sharing, and managing supplier and customer relationships. The extent to which the literature states these SCMPs positively contribute to achieving better firm performance, by enabling to achieve competitive advantages. Due to these techniques, there are various benefits such as low price/cost, reliable demand, product innovation, and quick time to market. The figure given below shows the proposed conceptual framework proposed for this study.

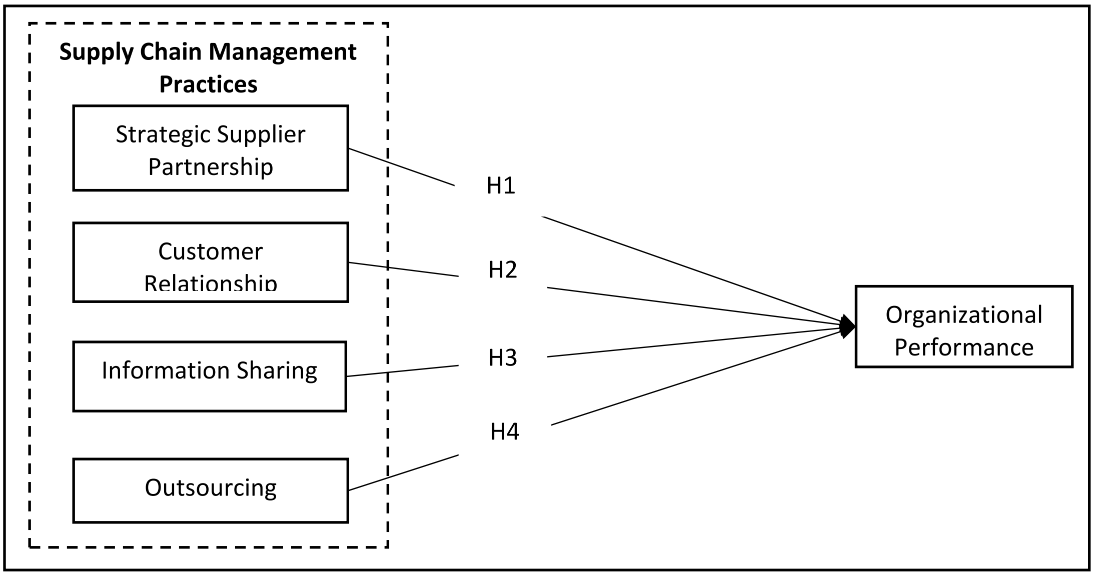

Fig. 1 Conceptual Framework

RESEARCH METHODOLOGY

The purpose of this study is to study how SCMP influences firm performance. On the basis of positivist ontologies, quantitative research is the preferred method. (Ryan, 2018; Wilhite et al., 2014). The primary data for this descriptive research study were gathered from the relevant department of FMCG companies in Pakistan and the research design was cross-sectional.

Sample

The target population for this study was experienced individuals working in various supply chain-related departments of FMCG companies in Karachi, such as general managers and managers in some cases assistant managers who have extensive experience and belong to departments like planning and supply chain, production, finance, purchase, logistics, or their equivalent. To distribute the questionnaire more broadly and widely, extensive collaborative efforts were begun with several supply chain professionals. A list of contacts of FMCG companies from the members of the Pakistan FMCG Association (PFMCGA) is developed for data collection purposes. As a result of joint efforts, a total of 2000 questionnaires were distributed to various FMCG companies, of which only 317 were received but only 231 were useable. This represents only a 11.6 percent response rate which is quite less than similar studies carried out in the specific area of SCMP and firm performance (Machado et al., 2019; Pournader et al., 2019) but in the acceptable range of more than 10%, as per (Cohen, 2013; Mugenda & Mugenda, 2003).

Data Collection and Instrument development;

In this research study, data was collected through a structured questionnaire using an online survey through a google form. Respondents were only contacted once and only received a maximum of two reminders for responses. The data for this cross-sectional study were collected during a period of 4 months (Feb 2022 to May 2022). The instrument was constructed to facilitate covering a spectrum of responses, from one extreme to the other. Therefore, a five-point Likert scale was used. To improve the instrument's validity and reliability, the data for the research variables were taken from a total of 20 different measurement items adapted from established instruments already employed in prior studies see Table -2.

Table -2 Instrument development.

Constructs	**No of Items**	**Sources**
SCM Practices		
Supplier strategic partnership	4	((Sukati et al., 2011)
Customer Relationship	5	(Shekhar & Uma Maheswari Devi, 2015)
Information Sharing	4	(Nag & Ferdausy, 2021)
Outsourcing	3	(Owiti et al., 2017)
Organizational Performance		
Organization Performance	4	(Omain, 2017)

DATA ANALYSIS AND RESULTS

The confirmatory factor analysis (CFA) approach is applied due to its conceptual strengths (Hu & Bentler, 1999). Survey items, CFA factor loadings and model fit statistics are shown in Figure 2, and all are under permissible levels as suggested by (Joe F. Hair et al., 2011). Although the model fitness indices, the RMSEA is 0.063, which is very close to 0.06, indicating a very good fit. The true value of RMSEA using a 90% confidence interval, its value must lie between 0.055 and 0.078, which is still below the cutoff value of 0.08, which further supports the model fit. The goodness of the fit of the model is further affirmed by normed chi-square = 1.52, below 2.0 and CFI = 0.94, indicating a very good fit. The value of SRMR is 0.063, which is above the conservative threshold of 0.05, but still very much below 0.09, which indicates an acceptable fit for a modal with more than 30 items and CFI > 0.92 (Joe F. Hair et al., 2020). These results show the unidimensionality of the scale as well.

Validity and reliability

Reliability was evaluated from Cronbach's alpha (CA) value and composite reliably (CR). The values of Cronbach's alpha in this model ranged from a minimum of 0.754 to a maximum of 0.831, which is quite above the minimum acceptable benchmark value of 0.7 (Du, 2010). Similarly, the composite reliability values were also well above the minimum required value of 0.7, ensuring that the measures were reliable (Babin et al., 2016). Further, Dijkstra-Henseler's rho (RhoA) was used as opposed to Cronbach's alpha and Composite Reliability generates a more precise estimation of data consistency (Ringle et al., 2020). To ensure the validity of the construct, multiple criteria were used.

Table 3. Constructs Cronbach Alpha (CA), composite reliability (CR), RhoA, and AVE.

Construct	**CA**	**CR**	**rhoA**	**AVE**
SCM Practices				
Strategic Supplier Partnership (SSP)	0.801	0.821	0.812	0.712
Customer Relationship (CR)	0.792	0.815	0.805	0.752
Information Sharing (IS)	0.827	0.832	0.830	0.811
Outsourcing(OS)	0.754	0.791	0.774	0.713
Organization Performance				
Organization Performance (OP)	0.831	0.852	0.842	0.792

Convergent validity, which describes the cohesiveness of indicators with their relevant measure, was assured from the values of outer loadings and average variance extracted (Williams et al., 2010). Also, all the values of outer loadings that measure indicator reliability were above the benchmark value of 0.6. The average variance extracted - AVE, the values of the third measure of convergent validity, are above the minimum required values of 0.5 (Liengaard et al., 2021). All the values of dependent and independent variables and their significance are shown in Table 4.

Results of the structural model analysis

To test the purposed hypothesis, we use structural equation modeling (SEM) on (SmartPLS-4). Figure 2 shows the result of the structural model analysis. The Index for the goodness of fit for the model under study is: X2 = 939.12; with df = 604; normed chi-square = 1.52; RMSEA = 0.053 90% confidence level for RMSEA (0.055 - 0.078); NNFI = 0.93; CFI = 0.94; SRMR = 0.059, these statistics represent a good model fit (Joe F. Hair et al., 2020). The values of the coefficient of determination (R2) represent the variances explained in each dependent variable and the predictive accuracy. The values of R2 for the dependent variable OP are closer to 0.5 showing good strength for the structural model (Joseph F. Hair et al., 2019). Also, the value of the f-square effect size is verified by effect size values; it shows the degree of importance of each path in terms of f-square values. The values of Q-square also help to show good predictive relevance of the model, since the values of all paths are above zero (Joe F. Hair et al., 2011).

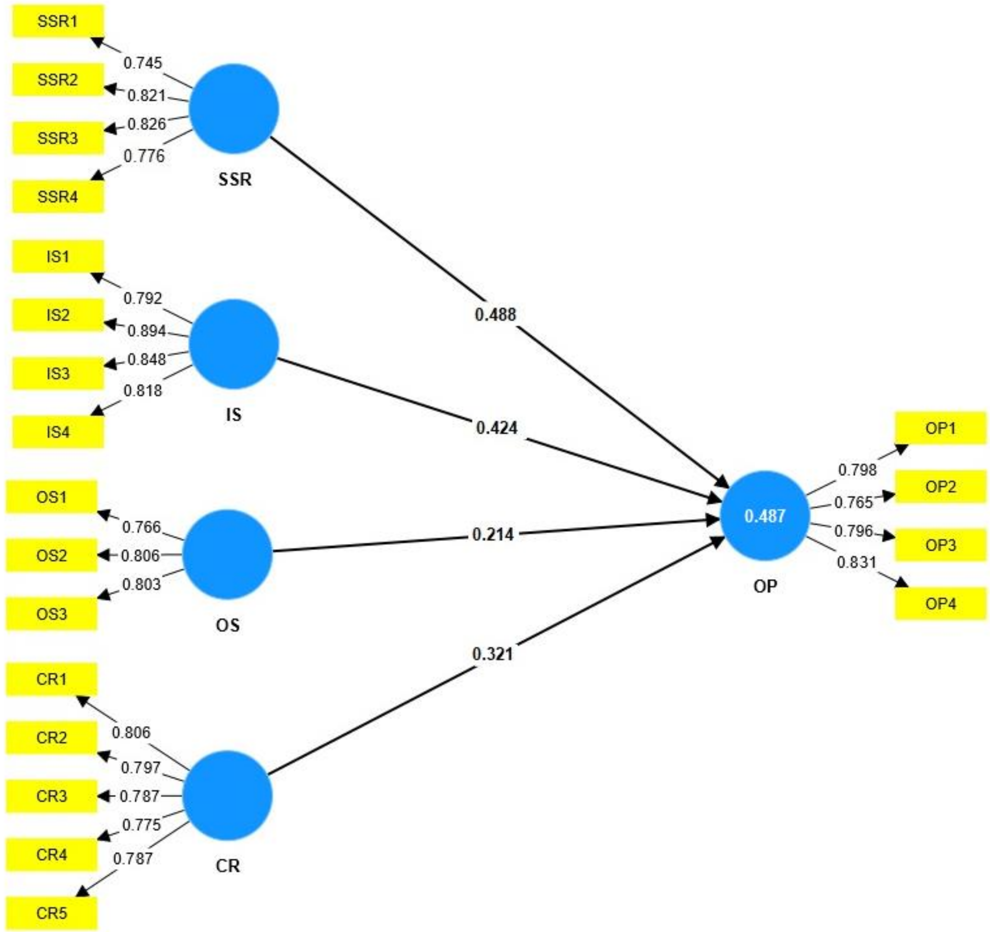

Fig. 2. Results of the structural model analysis. X2 = 939.12; df = 604; normed chi-square = 1.52; RMSEA = 0.053; NNFI = 0.93; CFI = 0.94; SRMR = 0.059. *p <0.01;

Final Model with Standardized Path Coefficient

In SmartPLS-4, the technique of blindfolding uses to compute Q-square. The Q-square results become more stable when the blindfolding technique was used at the omission distance of 7 and was found to be fairly higher than zero (Henseler et al., 2015). Since for each path the values of both Q-square and R-square are positive, hence the structured model is strong and of good quality (see Figure 2).

Table 4: Path Coefficients

Hypothesis	Structural path	Beta Value	(STDEV)	t -Values	p -values	Result
H1	SSP → OP	0.488	0.029	32.381	0.000	Accepted
H2	CR → OP	0.321	0.021	28.524	0.000	Accepted
H3	IS → OP	0.424	0.032	31.714	0.000	Accepted
H4	OS → OP	0.214	0.021	29.512	0.000	Accepted

The results obtained fully support the study expectations and the performance impact of SCM practices in FMCG organizations. In particular, the standardized path coefficients highlighted in Table 6 ensure a significant positive linkage between SCMP and firm performance and indicated that all proposed hypotheses are accepted by the current study. Especially the strongest path of supplier strategic partnership and organization performance in particular, with β= 0.488, p-value <0.01, with a t-value of 32.381. However, on the other hand, the weakest among the studied constructs of SCMP is outsourcing with β= 0.214, p-value <0.01, with a t-value of 29.512.

DISCUSSION AND CONCLUSION

Discussion

Based on a thorough study of the literature, it is estimated that integrating SCMP across the network will enhance the firm performance of FMCG companies in Pakistan. In this context, the primary goal of this study was to investigate the relationship between SCMP and firm performance. This proposition was investigated and validated by empirical evidence and it was determined to be significant. This study advances the literature on SCMP in several ways. First, we can prioritize the identified antecedents of SCMP specifically the FMCG industry. This study reveals that strategic partnership, customer relationship, information systems, and outsourcing increases the performance of companies that participate in the FMCG sector of the economy, which is also in alignment with previous studies. For example, according to (Kusi-Sarpong et al., 2016; Rehman Khan & Yu, 2019), the strategic supplier partnership (SSP) has a strong level of impact on firm performance, thereby creating the ability to achieve long-term relationships with suppliers. Additionally, organizations that seek strategic alliances with their key suppliers can work together and lower product costs while simultaneously raising supplier standards of enthusiasm, innovation, and product quality by reducing cost and time barriers (R. Kumar et al., 2014; Nag & Ferdausy, 2021). Further healthy relations with the customer are expected to increase the firm's market share, improve the competitive position, and ROI (Return On Investment) (A. Kumar et al., 2020). It is because information sharing connects one individual to other individuals (i.e., supply chain partners) and shares relevant information, so it ultimately enhances the overall firm performance (Guerola-Navarro et al., 2021) and also the outsourcing of any noncore function significantly increases the firm performance, both financially as well as non-financially (i.e. productivity). Thus, when SCMPs are embedded strongly in the firm strategy, firm performance is ultimately improved (Machado et al., 2019; Sukati et al., 2011). Second, organizations related to FMCG and implementing SCMP across their supply chain operations can demonstrate a considerable improvement in their performance (Alkalha et al., 2019; Gewald & Hinz, 2004). When organizations implement various SCMPs, the return on investment (ROI) can be increased to the desired optimized level, which helps the organization to achieve competitiveness. Moreover, FMCG companies need to strive to gain new cutting-edge competitiveness in highly agile manufacturing and short product life cycles, and to do so SCMP can prove to be very helpful. So, SCMP emerges as a tool to perform efficiently and effectively in today's competitive global market. Although SCMP helps organizations enhance their performance in several ways, companies also face certain hindrances and need investments for their implementation as well. But if organizations invest in effective ways to implement these practices, then firms would be able to achieve higher performance standards and competitiveness. On the other hand, if struggling organizations want to enhance their performance, they must adopt SCMP. Additionally, in the current global challenging competitive market, supply chain managers are compelled to improve the efficiency of their department; therefore, these SCMPs must be implemented effectively. On the contrary, for instance, the firm is under performance and unable to manage its supply chain network, indicates that various SCMP are either not followed or maybe not implemented in the true sense. Therefore, managers can use this model to identify the imbalances that hinder firms to perform at their full potential. Therefore, managers must use only those SCMP that can be adjusted according to their business needs and supply chain requirements, together with other practices that will consequently contribute to increasing firm performance. Furthermore, this study can be beneficial for organizations in understanding the critical impact of strategic supplier partnership and other SCMPs to improve firm performance. Despite the fact that SCMP can be adjusted according to firm needs, this study will prove to be a guide for managers and supervisors of organizations, by creating a deeper understanding of SCMP and its potential contribution to firm performance.

Conclusion

This research is a survey-based study to investigate the relationship between SCM practice and firm performance. The perspective considered in this study is aligned with the theory of resource-based view (RBV), which emphasizes that a unique set of resources owned by organizations is more likely to explain the variations in firm performance (Barney, 1991). Cross-sectional data were collected from FMCG companies in the largest metropolitan city of Pakistan. Due to too many competitors in the same product category, a shorter product life cycle and varying consumer demand make the firms unable to perform at their full potential (Rogers et al., 2016). In this study, various SCMPs, such as strategic supplier relationships, customer relationships, information systems, and outsourcing, are considered based on a resource-based view. Empirical findings reveal that SCMP has a significant positive impact on firm performance. Moreover, the findings reveal that among them, SSP and IS are the most important dimension of SCMP in the FMCG sector with 31.9% and 32.4%, respectively, of the variance in firm performance has been significantly explained. Therefore, if FMCG companies in developing countries want to improve their performance, should take into consideration these SCMPs and while taking various strategic moves, place special emphasis on supplier strategic partnership, customer relationship management, information system and outsourcing.

Research Limitations and Future Implications

Although the results of this study are comprehensive and justifiable, some limitations should be taken into account. First, the use of cross-sectional data restricts researchers to depict the entire materialization of both SCMP and organization performance. On the other hand, longitudinal data are more beneficial when studying performance variations over time. Second, this study considers four widely used SCMPs in Pakistan, but in future research, other important SCMPs such as integration, quality consideration, and postponement should be considered. Third, this study only considers the FMCG industry, whereas to make this model more generalized it should be applied to other industries as well as other cities throughout the country. Therefore, the results of the current study are limited to a particular area and industry. Future researchers are advised to focus on various industries and geographical areas to draw more detailed answers.

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ORIGINAL PAPER

REVERSE SUPPLY CHAIN OF RESIDUAL WOOD BIOMASS

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ABSTRACT. Background: Awareness of environmental or, more broadly, sustainable development is becoming an increasingly important issue, and questions of recycling and reuse have been getting more and more attention lately. Biomass is an important renewable resource and can take many forms, ranging from agricultural residues to food waste, forestry residues, and wood processing residues. A particular example is woody biomass such as forestry residues, wood-processing residues, or construction and municipal wastes that can be recycled and reused, providing a more environmentally friendly alternative to bioenergy production. This requires reverse supply chains in which the processes of collection, sorting, and transportation are efficient. The aim of this paper is to characterise the reverse supply chain of residual wood biomass and to indicate the main challenges related to it.

Methods: For the needs of the paper, the research was conducted using the methods of analysis of secondary and primary sources. The materials included data obtained from scientific papers, reports, studies, and internet sources. We conducted focus groups interviews (FGIs) in three cities in Poland.

Results: The article characterizes the details of the supply chain processes in woody biomass. Moreover, challenges, threats, and opportunities for reverse biomass supply chains are indicated.

Conclusions: Wood biomass can be derived from various residues and has a very wide range of industrial applications. Several factors must be considered when organising and conducting logistics processes for wood residues, such as origin, structure, and composition of woody biomass. The reverse supply chain of residual biomass consists of many different entities between which many different processes take place. The well-organized logistical and technological processes are vital parts of the supply chain because they result in size reduction, moisture adjustment, cleaning, fractionation, densification etc., which reduces transport and storage costs. There are many challenges related to biomass supply chains, e.g. the seasonality of biomass, the different requirements for handling and transport equipment, as well as storage space configuration.

Keywords: reverse supply chain; biomass; wood; residual wood

INTRODUCTION

In the past ten years, the EU countries have collectively produced between 40 and 60 million tonnes of wood waste yearly [Cocchi et al. 2019]. Recovery rates depend on both the country and the type of wood waste, but it can be seen that there is room for improving the current amounts [Garcia and Hora 2017]. This issue was recognized, and as a result, the amount of research dealing with residual wood biomass has increased over the past few years [Daian and Ozarska 2019].

Circular economy and sustainability of supply chains have received extremely relevant attention in the past years. Companies invest in optimizing their logistics processes and aim to reduce their environmental impact at the same time. These expenditures can reduce the companies' costs while also decreasing the amount of their environmental waste. One of the most important bottlenecks in increasing the use of biomass is the cost of logistics operations and technology for converting biomass into useful forms of energy. 20-50% of the cost of biomass supply is due to transport and handling operations [Rentizelas et al. 2019].

While the studies of the availability, life cycle, potential reuse of wood waste, and backward biomass streams [Sharma et al. 2013, Nunes 2020] have become more widespread in

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the past few years, the papers dealing with processes in reverse supply chains of residual wood biomass are still scarce [Sokhansanj and Hess 2009]. A brief analysis of the leading databases with the most important publications confirmed this. A search using the keywords “biomass" and “supply chain” or “logistics” in the Emerald database revealed 308 articles, in Sciencedirect (Elsevier) – 3517, and in Taylor & Francis – 431. Additionally, the keyword combination: “wood biomass” and "supply chain" or “logistics” gave the following results: 2, 166, and 17, respectively. When combined with the notion of a reverse process (“wood biomass” and "reverse supply chain" or “reverse logistics”), the results were even weaker: 1, 0, and 0.

The reverse supply chain redesign problem for wood waste from the construction industry was investigated in Trochu et al. [2018], and a MILP (mixed integer linear programming) model was proposed as its solution. A use-case on a scenario from Quebec, Canada, was also presented. In turn, Kot, S., & Ślusarczyk, B. [2013] drew attention to the relationship between the location of the biomass sources, the organization of the supply chain, and the economic and ecological results of energy production. Moreover, they analyzed the different biomass delivery methods [4]. There are also some works on biomass storage problems in the supply chain [Allen et al. 1998, Tatsiopoulos, Tolis 2003].

However, articles on circular economy are more numerous. For example, Araujo et al. [2019] assessed the literature on circular economy in wood panel production. The conclusion was that while circular economy as a concept was being investigated with regard to waste production in this sector, LCA (life cycle assessment) studies had mainly been carried out [Kim, Song 2013]. Daian and Ozarska [2009] studied a sample group of six SMEs in the wood furniture sector of Australia and collected data about the current state of their wood waste and its reuse, recycling and disposal. Based on this, they formulated suggestions for wood waste management. Studies comparing wood waste management in selected European countries were also conducted by Garcia and Hora [2017] and the BioReg Project [2017].

A good example of a business dedicated to circular economy is the global home-furnishing company IKEA. It was announced that they would develop circular capabilities in all their products by 2030 [2022]. This means that they would use only renewable or recycled materials, as well as give their products a longer lifespan through reuse, refurbishment, remanufacturing, and recycling. Evaluating the availability of residual wood biomass is also becoming more and more important, which can be seen from the multiple recent studies that have dealt with this issue. Research by Verkerk et al. [2019] and Borzecki et al. [2018] assessed the potential availability of forest biomass from European forests and its spatial distribution, focusing on the biomass hotspots.

Given the indicated scarcity of the research on reverse supply chains for woody bio-mass, the aim of this article is to characterise the reverse supply chain of residual wood biomass and to indicate the main challenges related to it.

RESEARCH METHODOLOGY

The research presented in this paper was carried out for a project which aims to develop a model of reverse supply chain of residual wood biomass. Achievement thereof is possible by conducting several stages of research, consisting of a literature review, empirical studies, and mathematical modelling. The empirical research was divided into two parts: research using a qualitative method and research using a quantitative one. The former aimed to analyse the issues related to the reverse supply chain of residual wood biomass and to provide information necessary for the appropriate design of the quantitative research, including, above all, the design of a survey questionnaire. This article uses the former type of research. A focus group interview (FGI) was applied as a technique for collecting information. Like other qualitative methods, it does not need to be conducted on representative samples of the population. For this reason, the selection of respondents for the study was purposive. The main criterion was to ensure that the participants were as diverse as possible in terms of experience. In addition, each participant in the study had to meet the condition of being familiar with the topic of residual wood biomass.

In July 2022, we conducted FGIs in three cities in Poland using questionnaires concerning working in companies related to the wood industry, sawmills, or involved in handling and recycling. The sample size was three groups, each of which consisted of 7 people.

The interview was conducted according to a prepared scenario, which was based on a literature analysis and collaboration with experts in wood (3 people) and logistics and supply chains (3 people). As a result, a scenario was prepared which consisted of questions and tasks for the respondents. The tasks were divided into 2 main parts, which, in turn, included several tasks: sources and uses of residual wood biomass (forms, sources, and use of residual wood biomass), reverse supply chain (essence, processes, actors, and problems). Some of these were carried out independently in order to activate all participants in the study, whereas others required joint effort in order to achieve synergies.

In the following part of the article, selected conclusions from the research have been presented. At the same time, their reference to the literature on the issues discussed has been shown.

WOODY BIOMASS

Wood is a raw material that has been used by humans almost since time immemorial. This is because it is relatively easy to obtain compared to other raw materials. Its wide range of applications is impressive. In fact, it is difficult to imagine industry and our daily life without it. Generally speaking, it is a raw material that is obtained from felled trees and shaped differently by processing. It also has other very important properties. Wood is a renewable, reusable, and recyclable material. Wood waste can therefore be reused and minimise the negative impact on the climate and the environment [Burnard et al. 2015].

Wood is one of the key elements of biomass. It accounts for around half of the European Union's total renewable energy consumption [Burnard et al. 2015]. Biomass has received a great deal of definitions. It is understood as "any organic material derived directly or indirectly from the process of photosynthesis by plants and algae, except for fossilized materials" [da Silva et al. 2018]. The range of possible uses for biomass is quite wide due to the very many existing materials that fit this definition [da Silva et al. 2018]. Another says that it "is one of the renewable energy sources on which policy makers are greatly based to reduce the greenhouse gas emissions" [Rentizelas et al. 2009]. The former definition focuses on the sources of biomass, while the latter emphasises the use of biomass.

Wood biomass can be derived from various residues. The respondents surveyed during the FGIs identified a number of these, which can be classified into three groups: agricultural and forestry residues, post-production residues, and post-consumer wood. In turn, the above can be divided into further categories [Kot, Ślusarczyk 2013, Burnard et al. 2015]:

1. Agriculture and forestry wood residues
   a. Stumpwood
   b. Forest chips
   c. Bark
2. Post-production residues
   a. Solid piece production residues
   b. Wood-based piece production residues
   c. Sawdust and chips
   d. Wood dust
   e. Bark as post-production waste
3. Post-consumer wood
   a. Wooden packaging
   b. Wooden elements of window and frame-woodwork
   c. Wooden interior elements
   d. Furniture / furniture elements
   e. Wooden waste from buildings and structures demolition
   f. Wooden elements of infrastructure/small architecture objects
   g. Wooden auxiliary elements for construction work

Biomass has a very wide range of industrial applications, and the respondents surveyed during the FGIs identified many of them. They can be classified according to use for, among others: production of wood materials, wood products, energy carriers, pharmaceuticals, cosmetics, chemical products, and even clothing and footwear [Tripathi et al. 2019, Khoddami et al. 2021]. Wood biomass is most commonly used for energy and particleboard production. However, according to European projects examining the topic (e.g. DEMOWOOD 2015, CaReWood 2015; FPS COST Action E31 2011), there is great potential to expand wood recovery for [Burnard et al. 2015] other uses [Khoddami et al. 2021].

The classifications indicated show that biomass has very different origins and uses. This poses major challenges for logistics [Kot, Ślusarczyk 2013].

REVERSE SUPPLY CHAIN

Reverse logistics and supply chain are fairly well-recognised concepts in the literature. There are several different definitions of reverse logistics. It is often referred to as the direction of the flow: “the process of planning, implementing and controlling backward flows of raw materials, in process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal" [Burnard et al. 2015]. Another approach pays attention to the type of thing that is the subject of the flow. It is “the continuous logistic process through which used products move from the consumer back to the producer or recycling enterprises” [Burnard et al. 2015].

The main goal of reverse logistics is to recover the value of returned materials or provide the means to dispose of them properly [Burnard et al. 2015]. It can be integrated with the traditional process of supply chain to guarantee both forward and reverse flows of resources (closed-loop supply chain) [Kazemi et al. 2019].

The reverse supply chain of residual biomass consists of many different entities. According to the respondents surveyed and literature [Rentizelas et al. 2009, Tripathi et al. 2019], the most common ones include:

1. Sawmills
2. Manufacturers of wood-based panels
3. Woodwork manufacturers
4. Manufacturers of wooden houses
5. Manufacturers of wooden packaging
6. Manufacturers of flooring materials
7. Furniture manufacturers
8. Cellulose plants
9. Recycling companies
10. Demolition companies
11. Transportation and logistics companies
12. Municipal waste collection companies
13. Land reclamation companies
14. Distributors of materials and/or final wood products

Many different processes take place between the actors indicated. Reverse logistics processes involved in residues according to the respondents surveyed and literature [Rentizelas et al. 2009, Burnard et al. 2015, Dekker et al. 2004] are as follows:

1. Field/forest transportation
2. Transportation (road, rail, sea, etc.)
3. Transshipment
4. Identification and marking/labeling of the type of raw material/wood biomass residue and product
5. Storage/warehousing

They refer to the processes throughout the handling of the raw material – both in-house and those outsourced to other companies.

In addition to the logistical processes, technological ones can be distinguished, which are closely related to the former. They are [Rentizelas et al. 2009, Burnard et al. 2015]:

1. Quality control
2. Sorting/selection
3. Drying
4. Cleaning
5. Processing
6. Composting
7. Combustion with energy recovery
8. Disposal

Both logistical and technological processes are vital parts of the supply chain because they result in size reduction, moisture adjustment, cleaning, fractionation, densification etc., which reduce transport and storage costs [Sokhansanj, Hess 2009].

Each of the logistics processes identified is important, but from the cost point of view, transport and storage are key issues [Rentizelas et al. 2009, Sokhansanj, Hess 2009, Kot, Ślusarczyk 2013]. In the case of transport, a distinction is made between short and long-distance transport. The former involves transport at the location of the biomass [Sokhansanj, Hess 2009]. Road transport is most often chosen because it is most flexible and has the greatest accessibility (a car can go almost anywhere, such as fields or forests). Heavy goods vehicles [Allen et al. 1998, Huisman et al. 1997] and agricultural/forestry equipment [Rentizelas et al. 2009, Tatsiopoulos, Tolis 2003] are primarily used here. When biomass needs to be transported over longer distances, it is done by other transport means, such as ship or train. Road transport is also used here, particularly when delivery times are important [Hamelinck et al. 2004]. While biomass is no more challenging than other things as far as transport is concerned, the situation is more complicated in the case of storage. Biomass is very often seasonal, i.e. it is produced at a specific time, e.g. after harvesting or felling. Due to the different forms of woody biomass residues, a different configuration of storage space is often required. Sometimes drying, cleaning, or composting processes are required. This creates a need for a storage point located on the farm or in the forest. They may then be stored at an intermediate site or with recycling companies, distributors of materials, and final products or other entities [Rentizelas et al. 2009].

Several factors must be considered when organising and conducting logistics processes for wood residues. According to the respondents surveyed, among the most important ones are the following:

- sources and sourcing of woody biomass residues (e.g. type of raw material supplier and number of receiving locations)
- origin, structure, and composition of woody biomass residue (e.g. contamination with post-consumer elements, chemical content, and presence of metals)
- required moisture content of the woody biomass residue and/or product
- required temperature of the woody biomass residue and/or product
- physical form of the woody biomass residue (dimensions, volume, weight, etc.)
- degree of risk of ignition of the woody biomass residue

CHALLENGES, THREATS AND OPPORTUNITIES FOR REVERSE BIOMASS SUPPLY CHAINS

In addition to the aforementioned seasonality of biomass and the different requirements for handling and transport equipment, as well as storage space configuration, other challenges of biomass supply chains can be distinguished. According to the respondents surveyed and literature [Kot, Ślusarczyk, 2013, Burnard et al. 2015], these include:

- large variety of types and forms of woody biomass residues
- high dispersion of woody biomass residues sites
- low utilisation value, low quality of woody biomass residues
- high purchase price of woody biomass residues
- high cleaning and processing costs of woody biomass residues
- relatively high cost of transport, handling, and storage of woody biomass residues
- lack of an information system on the availability of woody biomass residues
- high and very different requirements for combustion equipment with energy recovery
- low awareness (among producers and the community) of the potential for reuse of woody biomass residues
- In addition, many countries lack systemic and institutional solutions for the recovery of woody biomass residues, especially post-consumer wood, and a national classification of woody biomass residues to guide its use.

The situation in the wood biomass supply chain has been complicated by various events such as the pandemic, the war in Ukraine, and high inflation. As a result, a number of distinctions can be made here:

- problems with access to timber (e.g. harvesting restrictions)
- increase in timber prices
- increase in labour costs

- limited availability of staff with the required skills
- increase in transport costs (e.g. increase in fuel costs, vehicles, drivers' salaries)
- increase in processing costs (e.g. high energy costs)
- limited investment opportunities (e.g. lack of access to funds for infrastructure purchase)
- lack or long lead times for delivery of parts and equipment

Despite the current complex economic and social situation, it is worth identifying opportunities for reverse supply chains for woody biomass residues, namely:

- increasing the share of wood biomass in energy production
- innovative technologies and products using recycled wood raw material
- the development of a collection and recycling system for wood waste, especially post-consumer wood waste
- legislative changes to promote recycling, including putting into practice the classification of wood waste for recycling
- education of the community on the environmental benefits of wood products
- improvement/development of the EU's environmental policy and creation of new growth opportunities for wood biomass products
- new markets after the end of the war (reconstruction of Ukraine)
- introduction of segregation of waste from construction
- limiting (in some areas) the substitution of wood by its non-wood (less environmentally friendly) equivalents
- search for new possibilities and unique solutions in architectural design which take into account environmental aspects
- striving to reduce the unit cost of production by maximising the use of the raw material

CONCLUDING REMARKS

The management of residual wood biomass is an important field, and not many studies have dealt with the reverse supply chain. There are multiple problem classes that can be studied in the reverse logistics processes of wood. Optimizing the activities of this supply chain and identifying their special characteristics is a relevant issue both for reducing the environmental impact and for increasing the efficiency and profit of companies.

The goal of this paper was to identify the processes in the woody biomass supply chain and to indicate the main challenges and opportunities facing it. The conclusions in the article can therefore be regarded as a kind of state of the art. The next step will be to conduct empirical research in the form of computer-assisted telephone interviews (CATI). The results of such a study will allow new phenomena to be confirmed or rejected in the form of research hypotheses. Next, we plan to develop efficient models for the problems that will be investigated. There is a need for a study of reverse logistics problems connected to residual wood biomass and the development of efficient optimization algorithms for these problems. This is usually a very hard task for new domains, and innovative ideas for modeling will be needed. The optimisation of activities in this supply chain and the identification of their specific characteristics is an important issue both from the point of view of reducing environmental impacts and for increasing the productivity and performance of wood biomass businesses.

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ORIGINAL PAPER

RESEARCH OPPORTUNITIES IN TEXTILE REVERSE LOGISTICS: A SYSTEMATIC REVIEW

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ABSTRACT. Background: The textile industry generates a large volume of waste due to the increasing demand for clothing for daily use and fashion. To reduce waste, reverse logistics (RL) has been proposed to ensure the recycling and reuse of waste textiles in the value chain. RL has been broadly examined in several manufacturing supply chains but less explored in the textile industry. The absence of a systematic review on textile reverse logistics (TRL) makes it difficult to identify existing knowledge gaps and research opportunities.

Methods: Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, this paper contributes a systematic literature review of 28 relevant papers published on TRL between 1999 and August 2022.

Results: Overall, there is a shortage of recycling facilities in developing economies. There is a need for quantitative models that assess the location and potential disruptions and aversion of the resulting risks of TRL. Investigating consumers' perspectives on the desire to sort and transport old textiles to collection sites would be helpful to manufacturers. Additionally, system optimization to reduce emissions that emerge through the TRL production line would help reduce costs. It is also found that incentivizing clothing businesses that adhere to TRL practices would encourage more participation.

Conclusions: This study discusses research opportunities in TRL that are beneficial to the clothing and textiles industry and researchers in developing new waste management strategies.

Keywords: Textile Reverse Logistics; Textile Recycling; Textile waste management; Systematic review

INTRODUCTION

The textile industry is characterized by fast-paced fashion cycles coupled with consumers' lack of commitment to environmentally responsible buying habits [Gazzola et al., 2020; Hur, 2020; Pereira et al., 2021]. The proliferation of low-priced, mass-produced clothes from factories has led to wasteful consumerism and regular clothing and apparel discard [Gazzola et al., 2020; Hawley, 2009]. Fast-fashion retailing is defined by its emphasis on volume sales at discount prices, encouraging consumers to make regular clothing purchases. Consumers' propensity to acquire new items regularly and discard those still wearable promotes a "throwaway culture" [Joung, 2014]. The wasteful and excessive consumption is depleting our limited natural resources [Boryczko et al., 2014], which is problematic given that most of these resources do not regenerate. Consequently, numerous sustainability-related concerns emerge. Striving for resource conservation and zero waste in the textile industry is essential in order to address these concerns. Thus, the textile sector is under pressure to implement sustainable practices to reduce its adverse environmental effects. This increased pressure to implement environmental and sustainability practices has

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led to considerations for reverse logistics (RL) practices in the textile industry.

RL is the backward flow of products in the supply chain, employing a series of operations and processes for moving products from consumers to manufacturers due to defects or for recapturing values through recycling or remanufacturing [Banihashemi et al., 2019; Wadhwa et al., 2009]. RL enhances many aspects of supply chain management, including transportation, customer service, return processing, and inventory management, leading to new sources of income and more effective collaboration between manufacturers and suppliers [Li & Huang, 2021; Sharma et al., 2021]. Researchers and industrial practitioners are developing interests in RL due to its advantages to supply chain performance coupled with the increasing demands from stakeholders [Chauhan et al., 2022; Kitsis & Chen, 2021]. More ecologically concerned consumers and stringent environmental regulations set by authorities and competitors are beginning to pressure businesses to include environmentally responsible practices and RL processes in their strategic plans and operations [Govindan et al., 2015; Nik Abdullah, 2015; Vanalle et al., 2017]. These plans and operations deliver economic and environmental advantages by recapturing values from returned products as well as assisting companies to compete, particularly those facing fierce competition with thin profit margins [Elmas & Erdoğmuş, 2011; Uriarte-Miranda et al., 2018]. These greener production activities encourage a circular economy's goal of transitioning from a linear material flow model to one based on a closed-loop circulation of resources [Kalmykova et al., 2018] and result in increased sales income and decreased firm operating costs, allowing businesses to differentiate themselves from their competitors [Hashemi, 2021].

Implementing RL processes, particularly in the textile industry, improves a company's public standing by encouraging waste diversion [Di Vaio et al., 2022]. Waste diversion provides many product disposition options, such as direct reuse, repair, refurbishment, remanufacturing, recycling, incineration, and landfilling [Alarcón et al., 2020]. By implementing proper textile waste diversion through RL processes, the amount of waste sent to landfills can be reduced. The economy also benefits when the extra energy produced by incineration is put to good use. Studies on RL implementations in sectors such as the electronics industry [Atasu & Subramanian, 2012; Cole et al., 2018; Jauhar et al., 2021], the automotive sector [Kaviani et al., 2020; Makarova et al., 2018], the copier and printer industry [Savaskan & Wassenhove, 2006] and the pharmaceuticals industry [Narayana et al., 2019], have received increasing attention.

However, textile reverse logistics (TRL) has received relatively limited attention, mainly due to challenges in recycling textile waste, as discussed in some papers [Leal Filho et al., 2019; Wojnowska-Baryła et al., 2022]. Although many well-known researchers [Jäämaa & Kaipia, 2022; Matter et al., 2013; Pal, 2017; Pinheiro et al., 2019; Sinha et al., 2016] have contributed to the body of knowledge on TRL, no study has comprehensively examined and summarized all of the available research on the topic. Therefore, further study of the reverse logistics of textile waste is necessary. The importance of review papers in evaluating and appraising developments in a research field is crucial.

This study summarizes the current body of literature on TRL by contrasting and analyzing the key research foci of diverse authors, investigating and highlighting the significance and application of RL in domains of textile waste, and identifying potential areas for further study, which is currently lacking. To achieve this, we conducted a thorough systematic review of the literature published on TRL between 1999 and August 25, 2022. Furthermore, this study evaluates the most pressing and emerging research themes in the TRL literature. As such, the review adopts a multifaceted approach to identify leading journals publishing on TRL, the primary areas of interest, and the research methodologies adopted in the TRL literature.

The paper is organized as follows: Section 2 describes the approach adopted in this systematic review and defines the selection procedures and criteria. Section 3 presents the outcomes of the review in accordance with the standard four phases of LCA. Section 4 discusses the challenges of LCA on tires and research opportunities in the future. Section 5 concludes this reviewing study.

MATERIALS AND METHODS

We first developed our research objectives and search strategies to locate the relevant literature. The primary focus was papers archived in Scopus and Web of Science databases between 1999 and August 25th 2022. This scope was chosen because the publications on TRL started in 1999. These databases are justifiable by their prominence in academia, and publications indexed in them have undergone a thorough peer review. They are undoubtedly among the most dependable aggregators of high-quality scientific and academic publications such as journal papers, conference proceedings, and book reviews [Pranckutė, 2021]. In the second stage, we used a Boolean search with the following keyword combinations (textile) OR (apparel) OR (clothing) OR (garment) OR (fashion) AND (reverse) AND (logistics).

The following criteria were used to select the papers used in this review: (a) papers unrelated to the themes and objectives of our study were excluded; (b) only full literary works on textile reverse logistics published in the English language and indexed in Web of Science and Scopus were considered; (c) the scope included review papers, conference papers, and book chapters to incorporate all relevant literature on TRL.

The search was conducted on August 25th 2022, to ensure consistency across the two databases. It yielded 115 records from the two digital repositories utilizing the keywords. After eliminating duplicate papers (n=48), 67 publications remained. These publications included reviews, research papers, conferences, comments, and evaluation reports published between 1999 and 2022. In the next stage, we employed manual sorting or the Delphi method. Three researchers independently screened papers' topics, titles, abstracts, and keywords using various basic to advanced searches and query strings to eliminate irrelevant papers, leading to the removal of 39 papers. The remaining 28 papers qualified and were used for the review.

RESULTS

Overall, there were five papers (17.86%) published in Book Sections and Conference Proceedings each. Several journals have published one paper (3.57%). The total number of papers published can be grouped into five thematic areas covering environment and waste management of textile & fashion (50%), economics and business administration (28.57%), and operations management, and chemical and industrial engineering (21.43%). The diversity in these journals is an intriguing and remarkable trend that signals a rising interest in the TRL literature.

To understand the trend in TRL publications, we analyzed the number of papers published over time. The result shows that publication has been inconsistent for the past years. The highest number of publications was seen in 2016 and 2018, with four papers each. The scope of this review took in papers published between 1999 and 2022. This is because there was no literature on the topic before 1999. One paper was published in 1999, after which no work was recorded until 2011.

Even though there was a fluctuation in publications between 2016 and the first half of 2022, this period saw a significant increase in research activities in textile reverse logistics compared to previous years. This tendency may be considered a reflection of the growing interest in RL literature. Figure 1 depicts a yearly distribution of published papers between 1999 and 2022.

Figure 2 shows the total number of papers published by geographical distribution covering 14 countries. Six publications originate from China, four from Brazil, and three from India. Turkey, Sweden, the United Kingdom, and the United States contributed two papers, while Finland, Malaysia, Morocco, Germany, Portugal, Pakistan, and Iran contributed one paper each. Together, three BRICS countries (China, Brazil, and India) contributed 46.4% of the total publications in the study period.

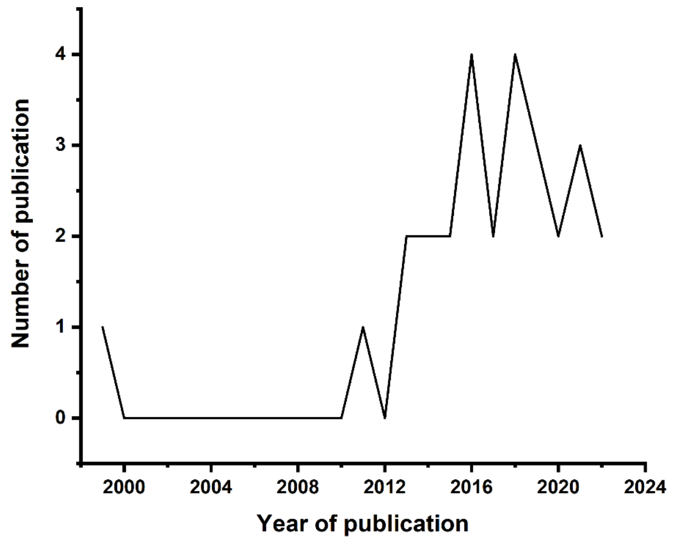

Fig. 1: The distribution of papers published over time

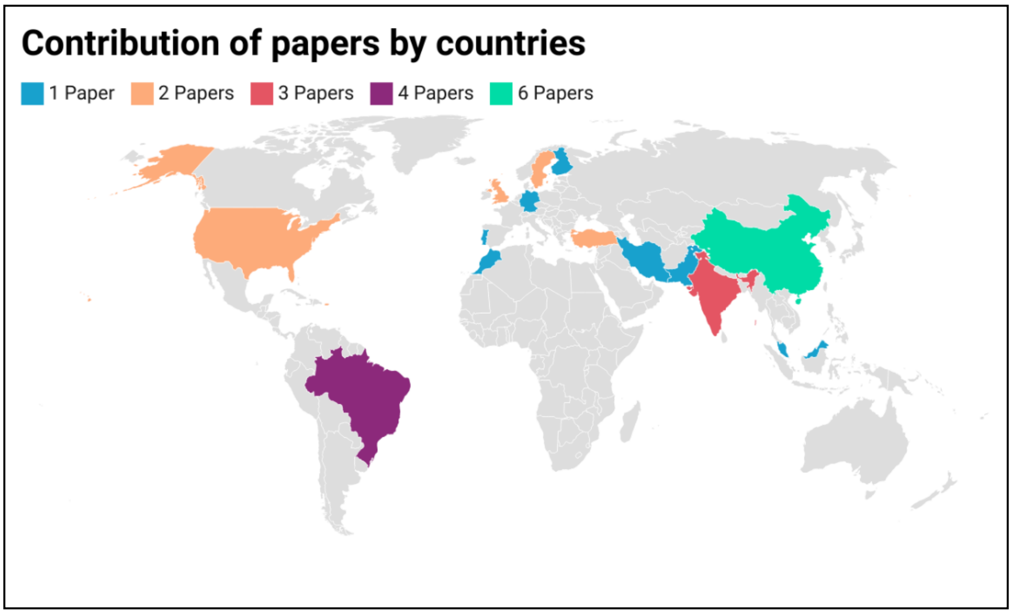

Fig. 2: Publications by countries

DISCUSSION

The papers have been classified into two categories. The first category is based on system optimization (n=9) using mixed integer linear programming (MILP), heuristics and hybridization, and game theory for cost optimization, supplier selection, and decision support. The second category includes qualitative research approaches (n=19). Studies in this category analyzed the current state of management and practices, identified challenges, and proposed recommendations and strategies. It also includes studies conducted through surveys, interviews, desk studies/reviews, field visits, and case studies, as presented in Table 1.

TRL has the potential to develop rapidly in a robust circular economy, which would increase the efficiency of resource usage, decrease environmental strain, and provide enormous economic rewards [Jäämaa & Kaipia, 2022]. However, these potentials are unachievable without stricter laws governing recycling practices [Liu & Yi, 2014]. Legal frameworks are essential for the T&A industry.

Considerations such as tightening regulatory framework requirements or establishing high ecological standards on the part of customers make RL crucial to tackling issues in the T&A industry [Zöllner et al., 2021]. They are beginning to significantly influence the development of RL processes in Europe, and a change in this trajectory would slow the growth of the recycling industry [Bouzon & Govindan, 2015; Zöllner et al., 2021]. Similarly, policy- and economy-related concerns were identified as the most influential factors for developing RL practices in the Brazilian clothing industry sector [Bouzon & Govindan, 2015; Pinheiro et al., 2019]. The decisions to implement RL for the textile industry are dependent on demands from government regulations and economic rewards, and the absence of these RL legislations makes Brazil a green awakening process for the management of used textile products [Bouzon & Govindan, 2015].

Despite the relevance of TRL, there is a shortage of recycling facilities in developing economies [Yan, 2019]. Recycling textile waste in developing countries is marred by poor collection and sorting mechanisms leading to high sorting, transportation, and logistics costs and no financial incentives resulting in an inefficient textile recycling culture [Garcia et al., 2019; Liu & Yi, 2014]. It is impossible to find solutions to these problems without robust TRL studies, the efforts of government agencies to execute RL and recycling, and the promotion of the positive effects of TRL processes [Abdulrahman et al., 2014; Garcia et al., 2019; Javed et al., 2021]. Many firms' motivation for implementing TRL processes stems from the potential financial benefits. However, economic viability in the TRL industry sector is significantly hindered by many fundamental constraints, including restricted technology, inferior recycled products, inefficient sorting mechanisms, etc. [Bouzon & Govindan, 2015; Pinheiro, 2018; Pinheiro et al., 2019].

Sorting recyclable textiles is particularly important in the recycling process [Dissanayake & Sinha, 2015; Realff et al., 1999]. Raising consumer awareness and facilitating an effective collection system lead to improved waste textile sorting [Zöllner et al., 2021]. Additionally, used consumer textiles are distinct from other domestic waste, such as glass and plastic, due to their material properties, requiring the development of ways to collect them in a manner that considers the unique characteristics of textiles and the limited means of collector entities [Jäämaa & Kaipia, 2022]. One way is by developing innovative technology that creates standardized sorting, grading, and disassembling processes [Dissanayake & Sinha, 2015]. Another strategy is offering customer incentives for returns at take-back places for used and old textile items to enhance recycling. The entire RL network is highly motivated by incentives through collecting recovered items, inspection, and forward/backward integration on RL networks [Garcia et al., 2019; Sorkun & Onay, 2018]. Incentives depend on the kinds of returns companies anticipate receiving from RL operations. Consumers' motivations to engage in RL activities are also affected by the location choice for collecting and inspecting returns [Sorkun & Onay, 2018].

Furthermore, insufficient communication and cooperation are crucial challenges among recycling companies preventing their TRL processes from reaching their full potential [Pinheiro, 2018]. However, forming partnerships with textile waste collectors and retailers can increase their output and reduce costs, since there are more synergies and spur innovations from the collaborations between sustainable designers, fashion retailers, and commercial waste collectors [Jäämaa & Kaipia, 2022]. The commitment of stakeholders and other players is necessary, but the involvement of collectors and customers is equally crucial to the success of TRL systems [Başaran, 2013]. The majority of inefficiencies experienced by recycling firms are attributable to the fragmentation and isolation of their respective processes [Abraham, 2011]. Building strategic partnerships based on, for instance, cloud alliance creates valuable and low-cost business models[Li et al., 2019] that enhance recyclers' profit maximization while decreasing collection and transportation costs (using the available return capacity of trucks in the same city) [Ahlaqqach et al., 2020; Torres et al., 2013]. The sharing economy and the use of light asset business models lead to the recycler's core competence and strategic partnerships to use the collective strengths of its members, such as access to resources and convenient locations, which are unachievable for recyclers operating alone [Guo et al., 2017; Li et al., 2019; Yan, 2019]. Thus, reverse logistics chain collaboration results in greater market knowledge, a more predictable business environment, and improved profitability [Abraham, 2011].

The high rate of return in the garments industry justifies a thorough investigation of upstream textile manufacturers. However, these examinations lack solid conceptual frameworks due to the scarcity of academic publications on performance measurements, especially Key Performance Indicators (KPIs) [Ahlström et al., 2020; Pal, 2017]. Developing performance measurement frameworks enable firms to access mitigation, gatekeeping, collection, sorting, and disposal indicators, allowing them to emphasize environmental sustainability, and can assist them in decision-making [Ahlström et al., 2020].

Most of the studies that employed a system optimization analysis of TRL mainly focused on cost optimization, with less emphasis on other system management processes [Ahlaqqach et al., 2020; Choi et al., 2018; Guo et al., 2017; Li et al., 2019; Singh et al., 2016]. In addition, several optimization strategies have been proposed to enhance decision-making to make the RL process more efficient [Ghanbarzadeh-Shams et al., 2022; Jain, 2016; Realff et al., 1999; Torres et al., 2013]. These models are necessary for understanding the RL network design, the optimization of return processing, the planning and scheduling of return products, the optimization of the secondary market, and the maximization of revenue from product disposition [Singh et al., 2016]. MILP is the widely used modeling method identified in the papers surveyed. It has broad adoption in the reverse logistics literature and was first employed in TRL by Realff et al. [1999]. Designing and developing mechanisms for collecting and reprocessing such a massive amount of valuable textile material is essential, particularly for supporting reverse logistics design and production decision-making processes [Ghanbarzadeh-Shams et al., 2022; Jain, 2016; Realff et al., 1999; Torres et al., 2013]. Notably, many of these models are insensitive to modifications in their variables. Such insensitivity leads to the unreliability of data capture and output prediction, affecting the volume of recyclable items and collection costs. Moreover, such a deficiency significantly affects profitability, defeating the purpose of TRL. Thus, optimizations that improve on the current scope is the first research opportunity identified.

Firms employing system optimization models see significant reductions in operating costs and increases in profit margins. This is especially true for smaller recyclers who purchase truckloads of unsorted items from various suppliers aiming to maximize earnings [Torres et al., 2013]. For such a smaller recycling facility, establishing flexible production schedules and deciding how many truckloads to buy and process from each supplier during a given period is cumbersome [Torres et al., 2013]. These challenges can be addressed by establishing coalitions among smaller recyclers [Ahlaqqach et al., 2020; Guo et al., 2017; Li et al., 2019]. The papers reviewed were lacking a more in-depth examination of how coalitions among recycling companies help lower their costs.

Many capabilities of RL directly impact the recyclers' performance, which positively affects their returns policies and cost positions. However, storage facilities, collection centers, and processing and disposal facilities incur high costs that must be considered when designing a TRL network. Even though Yan [2019] highlighted these costs, they were not extensively explored in the studies identified. Efforts to lower transportation and inventory costs are crucial because they make up a significant portion of the total cost of the reverse supply chain network [Singh et al., 2016]. Effective management of these cost positions creates positive relationships between strategic emphasis on TRL operations and the profitability of recycling activities, enabling recycling facilities to develop economic, organizational, marketing, and public relations balances [Realff et al., 1999; Singh et al., 2016]. Therefore, significant consideration must be given to exploring how information such as recyclable items' quality and location might be utilized to design reverse flows of used textiles. Furthermore, the uncertainty connected with recyclable product quality and variation linked with each player in the chain necessitates introducing different models that consider the development of stochastic techniques.

Some studies [Abraham, 2011; Choi et al., 2018; Jäämaa & Kaipia, 2022; Pal, 2017; Sorkun & Onay, 2018] were narrowly focused on their methodologies and data sourcing, limiting the ability to generalize their results. In addition, factors beyond the purview of these studies, such as regulations relating to product guidelines, were often given less consideration. They did not adequately capture the value development process or illustrate the varying impacts of many design components toward value creation. The studies also paid little attention to the viewpoints of final customers. Many studies did not specify the type of textile studied. Furthermore, many failed to adequately account for crucial factors, including location (collection sites, warehouses), potential disruptions, and the specific business practices of remanufacturing and recycling firms throughout the supply chain. Additionally, many of the studies did not go deeply enough to investigate the inclusion of the upstream textile supply chain players with reverse logistics players.

Unlike Brazil, where few studies tend to address firms' and consumers' corporate social responsibilities [Bouzon & Govindan, 2015; Garcia et al., 2019; Pinheiro, 2018], the rest lack or fail to discuss aspects of social responsibilities adequately and topics on CO_2 emissions were rarely addressed. Many of the firms mentioned in the identified studies are independently run, with weak connections with textile waste collectors and retailers. Incorporating social sustainability considerations and connecting with textile waste collectors and retailers could help them increase output, spur innovation, and reduce costs in the supply chain. A major barrier to achieving RL goals and social sustainability is the public's lack of understanding of environmental protection, especially consumers' lack of information on take-back channels for end-of-life items, which was not addressed in many of the studies. Due to small sample sizes, several papers could not fully investigate the correlation between enterprises' RL goals and the structures of their RL networks.

The concept of a closed-loop system with recycling is the primary solution for assisting the garment industry in addressing these challenges. However, even though the closed-loop system is broadly examined in other reverse manufacturing supply chains, it is less explored in the T&A industry. The absence of extensive research in the textile reverse supply chain has led to knowledge gaps. In addition, there are many uncertainties regarding the recovery of waste materials through recycling and the timing of their arrival, the quality of the recycled products in comparison to virgin ones, the demand for manufactured goods, the cost of remanufacturing, and the complexity of the remanufacturing operation considering logistics, inventory, and production planning.

Regardless of these lapses, developing nations stand to benefit economically from the textile reverse supply chain operations, as they bring about innovations and employment opportunities. The economic reasoning behind the cooperation and integration of services may be understood in broad strokes if these aspects are defined in the recyclers' value offered to consumers and partners. The practice of recycling textiles has the potential to have significant environmental and economic advantages. Considering the current state of the textile waste recycling industry across many developing countries, it is crucial that a comprehensive textile recycling and reuse system be established. This is crucial because the accumulation of unwanted textiles in these countries has long been a source of social unease. One way to contribute to this establishment is by conducting robust studies.

CONCLUSION

In conclusion, this study reviewed 28 relevant papers on TRL published between 1999 and August 25th 2022. The results of this research provide a more in-depth comprehension of TRL using the systematic representation of archival material across essential TRL themes. This research contributes to the academic discourse on TRL literature by capturing the literary growth of the field. Additionally, it provides input to policymakers in TRL design and policymaking. The results of this study also shed light on potential future areas of attention.

The results show that there is a need for more research regarding the strategic process of value creation and adoption in the TRL context, the development of quantitative models for measuring the effects of attributes and enablers with measurable levels of value, and an in-depth study on business models. These processes contribute to TRL literature by developing methods that stochastically assess the location and potential disruptions and aversion of the resulting risks. Future studies should investigate consumers' perspectives and desire to sort and transport old textiles to collection sites. Such initiatives would give a deeper understanding of the mechanisms that make textile sorting appealing to consumers, as efficient waste textile sorting is crucial for the smooth operation of a TRL system.

Further studies are needed on system optimization to examine the connection between TRL systems and other RL functions while also considering the number of emissions the TRL processes produce. More investigations of TRL processes, particularly in developing countries, are required to unearth possible alternatives for ideal management strategies. These investigations are necessary as they mandate clothing businesses to consider the most crucial RL drivers influencing their management processes. Studies employing large sample sizes and those providing international comparisons among TRL processes are needed to provide in-depth knowledge of how coalitions amongst recycling companies might help lower operating costs.

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ORIGINAL PAPER

MOST SUCCESSFUL BUSINESS MODELS IN LOGISTICS INNOVATIONS – THE REVIEW OF CROWD LOGISTICS SOLUTIONS

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ABSTRACT. Background: Crowd logistics is a relatively new phenomenon that has emerged due to the growing demand for flexible, efficient, and sustainable delivery solutions. This paper presents an empirical study of crowd logistics initiatives by collecting a comprehensive dataset of companies operating in this field. Our research aims to identify the elements of the most successful crowd logistics business models and identifies the causes for their failures.

Materials and methods: To achieve these goals, we conduct a systematic screening of the world market, which allows us to identify a diverse set of crowd logistics initiatives, ranging from small startups to well-established companies. We then classify these initiatives based on their business models, main business areas, and services. We also review the EU-funded projects related to the development of crowd logistics. Finally, we analyze the main business areas of each initiative, such as urban logistics, last-mile delivery, and transportation of goods.

Results: We present the full view of crowd logistics solutions worldwide, their main characteristics, and models to build a complete picture of those solutions and assess them as being successful or unsuccessful by providing the list of the features identified as success factors and failure factors.

Conclusions: Finally, we conclude that crowd logistics, despite many failures observed worldwide, can be a successful solution for urban logistics if it meets the requirements mentioned in the results section. Our findings provide insights into the emerging landscape of crowd logistics and offer practical implications for managers, policymakers, and researchers.

Keywords: crowd logistics, sharing economy, urban logistics, urban flows, crowdfunding

INTRODUCTION

In the literature on innovation, no single theory explains how innovation occurs. It is a research area constantly evolving due to economic development. In the context of logistics innovations, various theories should be considered to help explain and understand the ongoing process. Logistics innovation literature covers the most suitable approaches to this topic, such as Schumpeter's creative destruction concept, theory of S-curves, network theory, or resource-advantage theory [Grawe 2009]. Moreover, a few concepts are perceived as innovative within the sharing economy, e.g., crowd logistics (CL).

CL is a concept that leverages the power of the crowd to provide logistics services. CL has emerged as a new way of organizing and optimizing last-mile delivery (L-MD) in urban areas. The idea is based on the sharing economy model, where individuals or businesses can offer their unused resources and capacities, such as space in their vehicles or storage facilities, to provide different logistics services to others. The concept has recently gained considerable attention due to the increasing demand for fast and efficient delivery services, particularly in urban and suburban areas. However, there is still no homogeneous approach to defining CL, its essence and scope, no classification of successful business models, and no determination of elements which would allow it to achieve success. In this paper, we fill these gaps.

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This paper's aim is to discover the characteristics and elements of the most successful applications as the elements of business models for CL solutions operating on different continents. We begin by defining the logistics innovation, CL concept, and its key characteristics. Then, we examine the advantages and challenges associated with CL, such as cost-effectiveness, scalability, and reliability, as well as the potential impact on traditional logistics models. Next, we present the results of the analysis of the features of failed CL projects and successful implementations, providing the list of must-have elements. Finally, we offer insights and recommendations for practitioners and policymakers interested in adopting or regulating CL. In summary, this paper contributes to the ongoing debate on the potential of CL. By providing a comprehensive overview of the concept, its advantages, challenges, and current state of adoption, we hope to facilitate a better understanding of the potential of CL for smoothing the flows of goods in urban and suburban areas.

THEORETICAL BACKGROUND

Innovations

Schumpeter's approach related to economic development, entrepreneurship, economic cycles, and creative destruction has become a permanent part of the considerations regarding innovations. Schumpeter divided innovations into six types [Schumpeter 1934, Schumpeter 1942]:

1. launch of a new product/service or a new species of already known product/service
2. application of new methods of service or production or sales of a product (not yet proven in the industry)
3. opening of a new market (the market for which a branch of the industry was not yet represented)
4. acquiring new sources of supply of raw material or semi-finished goods
5. new industry structure, such as the creation or destruction of a monopoly position
6. application of the new organization of industry

The above approach has become the basis for distinguishing several types of innovation over the last decades. Public actors, stakeholders, and authorities creating legal frameworks were not without significance for isolating the above types of innovations.

Schumpeter believed that innovation is an essential driver of competitiveness [Porter and Stern 1999] and economic dynamics [Hanush and Pyka 2007]. He also believed that innovation is the center of economic change, causing gales of "creative destruction" [Schumpeter 1942]. Rapid technological change referring to Schumpeter's theory also appears in the resource-based view of the firm, which has evolved to a dynamic capabilities framework where innovation can be characterized as a dynamic capability [Grawe 2009].

A similar reference can be observed in the case of "radical innovations" placed in the exploration-exploitation framework. In this instance, radical innovations are designed to meet the needs of new markets and require new knowledge or a departure from existing knowledge within a company. Such innovations are incremental and designed to meet the needs of existing customers or markets and are characterized by refinement, implementation, and efficiency [Cheng and van de Ven 1996, Grawe 2009].

Knowledge management is the second theoretical framework for considering innovation. As a strategic resource for supporting the logistics innovations globalization of logistics processes, development of collaborative logistics partnership, the role of human resources, and the digitalization of logistics processes have been proposed [Lönnqvist 2017]. This framework also highlights that knowledge's uniqueness is fundamental in developing a sustained competitive advantage [Turner and Makhija 2006, Grawe 2009].

The third theory related to logistics innovations is the S-curves theory. It explains the origins and evolution of radical innovations, where consumer benefit is created in the introduction phase, benefits increase as the technology develops, and benefits increase at a slower rate as the technology enters maturity

[Christensen 1992, Chandy and Tellis 2000, Grawe 2009, Lee and Trimi 2021].

A reference should also be made to the network theory and resource-advantage theory. Network theory framework concerns position, power, embeddedness, and density in long-term inter-actors' relationships. Network theory research has also considered the roles of each actor in a network and the resulting impact on innovation [Dhanaraj and Parkhe 2006, Grawe 2009].

According to resource-advantage theory, companies and individuals use their resources to gain a competitive advantage against competitors, which in turn will lead to above-average financial results [Hunt and Morgan 1996]. Mentioned resources include a firm's assets, processes, information, and knowledge that can help a company improve efficiency and effectiveness [Barney 1991]. According to the resource-advantage theory, companies' primary goal is superior financial performance, which can only be attained by achieving a competitive advantage in the marketplace by implementing innovations [Hunt 2002, Grawe 2009].

Crowd logistics

The transition towards CL and sharing mobility contribute to the goals of low- and zero-emissions economies [Cohen and Kietzmann 2014]. Urban areas are seen as critical centers of sustainable growth [Ly 2020]. Commonly it is indicated that the sharing economy is the future for cities, especially its multimodal integration and optimization of the use of means of transport [Nikitas et al. 2017].

CL is a relatively new phenomenon, and a limited but growing body of literature exists on this topic. The genesis of CL was between 2000 and 2008, when the term first appeared in the literature. Initially, the term 'crowdsourcing' was used to refer to bottom-up initiatives, a form of online community and many more areas further adopted it. CL originated from crowdsourcing and means leaving logistics tasks to the 'crowd', i.e., the individuals who might be both service providers and customers [Carbone et al. 2017]. In this way, it can be defined as crowdsourcing in logistics. The development of the CL concept occurred during the rapid growth of the Internet, which enabled people to communicate with each other on social networks and platforms. In 2008, the company Uber started its operations, first as a shared mobility initiative, later enhanced to parcel and food deliveries. Since then, CL has started to become more business-like. CL should be understood as a part of sharing economy but both concepts constantly change in definition and their relations are no longer as sharp as they were a couple of years ago. Nowadays, CL solutions are also broadly known as crowd shipping but should be defined broadly since they include solutions dedicated to urban mobility [Buldeo Rai et al. 2017].

In the literature and other sources, there is one dominating approach to CL. The most accepted and complex definition of CL states that it "designates the outsourcing of logistics services to a mass of actors, whereby the coordination is supported by technical infrastructure" [Mehmann et al. 2015]. Following this approach, CL helps to benefit all stakeholders (not necessarily in the matter of money but time optimization or convenience). One of the key features of CL is its reliance on the crowd (a number of individuals and/or companies) to perform the delivery tasks, instead of traditional logistics providers. The individuals from the crowd are willing to transport goods using their own vehicles, bicycles, public transport, or even walking to deliver the parcels. This approach has several advantages over traditional logistics models, including lower costs, increased flexibility, and reduced environmental impact.

CL has emerged as a promising solution for L-MD and more generally, short-distance delivery, leveraging the collective efforts of individuals and businesses to transport goods more efficiently and sustainably. However, despite its potential benefits, many CL initiatives have failed to gain traction and achieve long-term success. The reasons behind these failures are often attributed to defects in the implementation process, such as inadequate technology or insufficient planning. However, some argue that external factors can also significantly impede the success of CL initiatives. In this paper, we examine the factors contributing to the failure of CL initiatives and explore whether these failures result primarily from defects in the implementation process or a matter of misfortune. By identifying the root causes of these failures, we aim to provide insights for logistics industry stakeholders to help improve future CL initiatives' success rate.

Defects in the implementation process may include inadequate technology, insufficient planning, or poor execution. For example, a CL platform may lack the necessary features to match supply and demand effectively, leading to inefficient routing and suboptimal deliveries. Alternatively, inadequate planning may result in a mismatch between demand and supply, leading to either overcapacity or underutilization of resources. Finally, poor execution may manifest in delays, low-quality service, or poor communication, leading to decreased user satisfaction and, ultimately, failure.

However, external factors may also contribute to the failure of CL initiatives. These may include changes in market conditions, such as shifts in consumer behavior or the emergence of new competitors, that render the existing business model obsolete. In addition, unforeseeable events such as natural disasters, pandemics, or economic downturns may also disrupt the normal functioning of a CL platform, leading to decreased user engagement and, ultimately, failure.

Several studies have examined the potential benefits of CL. For example, Nijden and van Meerkerk [2017] conducted a study in the Netherlands and found that using crowdsourcing in logistics could reduce delivery times and costs while increasing customer satisfaction. Similarly, Klumpp [2017] investigated the use of crowdsourcing in urban logistics and concluded that it has the potential to reduce delivery costs and carbon emissions significantly.

Despite its advantages, CL also faces several challenges. One of the main challenges is the lack of control over the delivery process, as the crowd is not a formal logistics provider and may not have the same level of expertise or reliability as traditional logistics companies. This challenge can be addressed by using technology platforms that provide real-time tracking and monitoring of deliveries and by implementing quality control measures.

METHOD

Research procedure

To collect data on different initiatives of CL, we adopted a systematic approach to screen the world market. First, we conducted a comprehensive literature review of peer-reviewed articles, conference proceedings, and industry reports related to CL. This review allowed us to identify a preliminary list of CL initiatives and their associated business models. We then used this list as a starting point for our data collection.

Next, we used a combination of online search engines and business directories to identify additional CL initiatives. We searched for companies operating in various geographical regions, including North America, Europe, Asia, and Australia. We used a variety of keywords in abstract search, such as "crowd logistics," "peer-to-peer delivery," "collaborative logistics," "on-demand delivery," and "crowd shipping" to ensure that we captured a diverse range of initiatives.

Once we identified a potential CL initiative, we conducted a more detailed analysis of its business model and main business area. We collected data on the following aspects of each initiative:

1. Business model: We identified the type of business model adopted by each initiative, such as peer-to-peer (P2P) networks, on-demand delivery platforms, and collaborative logistics networks.
2. Main business area: We assessed the main business area of each initiative, such as urban logistics, last-mile delivery, and transportation of goods.

To ensure the accuracy and completeness of our dataset, we cross-checked our findings with publicly available information on company websites, industry reports, and news articles. We also consulted with experts in the field of CL to validate our findings.

In total, we collected data on over 50 CL initiatives worldwide (see Table 1). We analyzed the data using descriptive statistics and presented our findings in tables and charts. Our results provide a comprehensive overview of the emerging landscape of CL and offer insights into the most prevalent business models and main business areas.

Table 1. The list of identified CL initiatives

Solution	***Country***	***Main scope***
Airmee	Sweden	Carbon free delivery
Axlehire	USA	Improve logistics services
Bitsout	Spain	Smart tools
Boxconn	Ghana	Improve logistics services
Bringg	Israel	Last-mile delivery solutions
Clean Motion	Sweden	Improve logistics services
Convoy	USA	Carbon free delivery
Darkstore	USA	Last-mile delivery solutions
Deliverr	USA	Improve logistics services
Delhivery	India	Smart tools
DroppX	Finland	Last-mile delivery solutions
EasyPost	USA	Smart tools
Everstock	Germany	Improve logistics services
Fabric	USA	Smart tools
Flash Express	Thailand	Improve logistics services
Flock Freight	USA	Improve logistics services
Hive Logistics	Europe (many locations)	Improve logistics services
Juma Peisong	China	Last-mile delivery solutions
Lizee	France	Smart tools
lock Freight	USA	Smart tools
Loggi	Brazil	Smart tools
Mastery Logistics Systems	USA	Smart tools
MVXchange	Niger	Improve logistics services
Navines	Israel	Smart tools
Nuvocargo	Mexico	Smart tools
Onfleet	USA	Smart tools
Report a Car	Saudi Arabia	Improve logistics services
Stone Rooster Distributors	USA	Improve logistics services
Tyltgo	Canada	Last-mile delivery solutions
Volta Trucks	United Kingdom	Improve logistics services
w8time	Canada	Smart tools
WareIQ	India	Last-mile delivery solutions
Yimidida	China	Smart tools
Zeus Labs	United Kingdom	Improve logistics services
Zoodbox	Canada	Last-mile delivery solutions

Source: own elaboration.

In the screening process, we identified most of the CL solutions to be started in EU countries (we recorded the highest number of failures in this geographical area but also many successes). To screen EU-funded projects related to CL, we adopted a systematic approach that involved searching multiple databases and using specific keywords to identify relevant projects. We used the following steps to conduct our search:

1. Identification of relevant databases: We identified several databases that contained information on EU-funded projects, including the European Commission's CORDIS database, and additionally, TRIMIS database.
2. Selection of keywords: We selected a set of keywords related to CL and its associated concepts. These keywords included "crowd logistics," "crowdsourcing," “crowd shipping”, "collaborative logistics," "on-demand delivery," "urban logistics," and "last-mile delivery."
3. Filtering and selecting projects: We filtered the search results based on several criteria, such as the project's relevance to CL, its funding source (i.e., EU funding), and the project's stage of development (i.e., ongoing or completed). We also excluded projects that were not related to logistics or transportation.
4. Data extraction: Once we had identified relevant projects, we extracted data on their key features, such as their project title, duration, funding amount, consortium members, and main research areas. We also collected information on the project's approach to CL, including their business model and main business area.
5. Data analysis: We analyzed the collected data using descriptive statistics and visualizations. We also conducted a qualitative analysis of the project descriptions and the content of the projects’ websites to identify the main research areas and approaches adopted by each project.

Our systematic approach to screening EU-funded projects related to CL enabled us to identify and analyze a comprehensive dataset of relevant projects. Our findings provide insights into the current state of crowd logistics research and the various approaches being pursued by EU-funded projects in this field.

Qualitative review

Additionally, a few more reviews were prepared to achieve the research goal:

- Review of solutions
- Review of business models
- Review of lifetime of those solutions

Review of solutions:

The review of solutions is a research method that involves analyzing existing solutions that have been proposed or implemented in a particular CL solution. The materials are then analyzed to identify common solutions, as well as the strengths and weaknesses of the solutions, e.g., regarding using the IT tools or particular functionalities.

Review of business models:

The review of business models involved analyzing the various business models that are used by CL companies—usually providers of IT applications. We collected data about the pricing model, prices for using the IT application, payment models, etc.

Review of lifetime of those solutions:

Reviewing the lifetime of those solutions involved gathering relevant information on CL initiatives that have been implemented, including their start and end dates, as well as any factors that contributed to their success or failure. We identified commonalities and differences between the initiatives and the factors contributing to their longevity or lack thereof. The longevity of solutions meant successful implementation and accepting the solution by the market.

RESULTS

Crowd logistics solutions

As mentioned earlier, many CL solutions failed. We identified 35 successful CL solutions being launched from 2010 to 2021 (we identified that the failures of CL solutions were observed in 93% of failures in the first 2 years after launching the solution, so those that survived the first 2 years were considered successful). CL is developing most rapidly in the United States and Canada (see Figure 1). Nine solutions have been located in EU countries, but no single country reports many solutions. Also, Europe has the highest score of failed solutions and the highest number of started CL initiatives. Therefore, Europe is perceived as an accelerator and testbed for CL solutions.

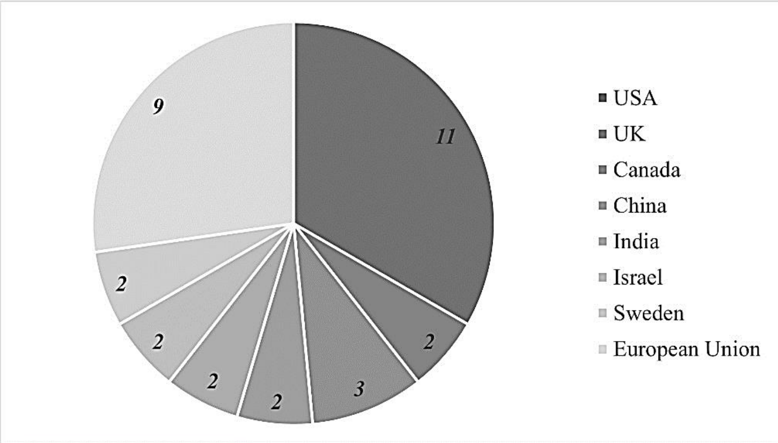

Fig. 1. Number of crowd logistics solutions identified in the respective countries
Source: Own elaboration.

Specific solutions were examined regarding the organization's purpose, year, and country of establishment. The oldest still-existing solution, Clean Motion, was implemented in Sweden in 2010. In the following years, CL development moved from Europe to the USA and Canada, which is linked to North American countries' economic and social development.

Then, all the existing CL solutions were analyzed (see detailed results presented in Appendix). The main findings are as follows. Implementing CL solutions requires several conditions to be met: (1) a well-developed technical infrastructure, (2) a well-developed crowd network, i.e., connections between community members, (3) high capacity and the possibility of voluntary work, (4) unidentified nature, (5) remaining external to the organization, and (6) the existence of some sort of compensation for the work performed [Buldeo Rai et al. 2017]. Technical infrastructure refers to several types of infrastructure essential for logistics processes in general and digital infrastructure, high-speed internet public infrastructure, mobile applications, and other similar infrastructures. Thus, the development of CL is mainly concerned with networks of connections between the organization, users, and customers, which requires high-quality social resources.

The analysis of the identified CL solutions has highlighted specific areas necessary for developing these solutions (Figure 2.).

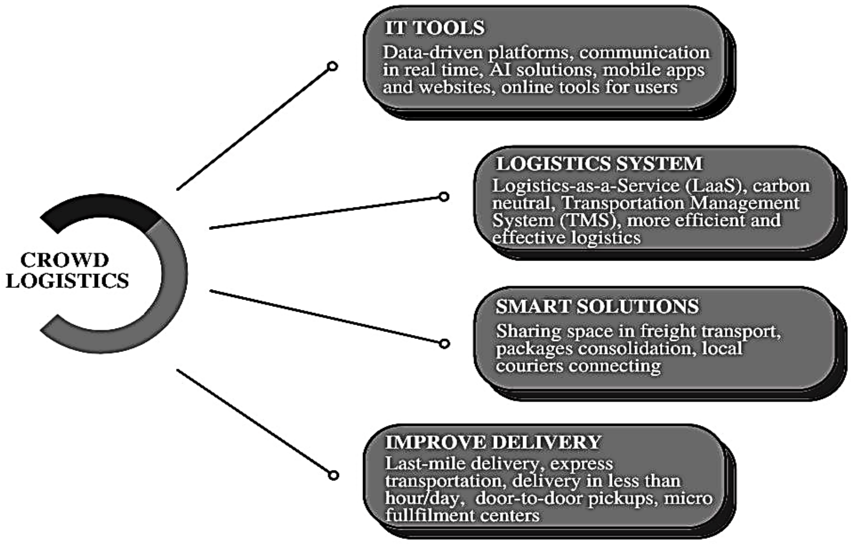

Fig. 2. Key areas for the crowd logistics development
Source: Own elaboration.

Key areas for successful implementation and growth of CL are developing IT tools, the logistics system itself, the development of smart solutions, and improvement of processes. IT tools need a lot of data provided in real time. Data-driven platforms and algorithms are the most important part of a CL system; they offer the constant, ongoing monitoring of the free capacities of the crowd. The most successful CL solutions in this regard included Bringg (Israel), Convoy, Flock Freight, Fabric, Mastery Logistics System, Onfleet (USA), Delhivery (India), DroppX (Finland), Everstock (Germany), Loggi (Brazil), Nuvocargo (Mexico), Ymidida (China), and Zoodbox (Canada). IT tools, mainly available for laptops and (especially) different mobile devices, help connect stakeholders in the system and make it possible to create new actions using Artificial Intelligence (AI) or cloud-based mobile applications. The same stakeholder may become the service provider and customer in one transaction at the next time. Many price models are developed in the identified solutions, starting with the pre-paid systems, lump sums, fixed wages, and flexible agreements between the users and the crowd. There is no gold standard in the analyzed models; however, the most often used is the system with capacities in the form of an offer published by the CL service provider together with the wage or lump sum for the specific service from the offer.

The core of the successful implementation of CL is the structure of the offer. The logistics system needs a new paradigm to meet ecological standards and stakeholders' needs. Therefore, emerging companies need to demonstrate a new perspective on logistics, as in the case of Everstock (Germany), which based its growth model on the Logistics-as-a-Service concept (LaaS). A LaaS solution is an approach that presents holistic logistics, where the company treats the delivery process as a service that uses different means and modes of delivery. Therefore, even if the service needs to involve different solutions to be implemented, it will be planned and delivered using the complex offer. Moreover nowadays, logistics processes, especially delivery, should be based on environmentally friendly solutions. Furthermore, improving process efficiency following the direction of customer expectations is also a significant growth factor for companies. Then, the most successful CL solutions we analysed provided the basic data analytics for users, helping them monitor the times, costs, and performance (if they are service providers or customers). Also, data can be exported in Excel format to be further used by the user if they want to analyze the data independently.

Another critical element of the CL is allowing the use of smart solutions as a part of the previously mentioned CI IT application– especially sharing space, consolidation of parcels, or solutions to connect couriers. Such solutions have been implemented by companies such as Deliverr, Flock Freight, Onfleet (USA), DroppX (Finland), and Loggi (Brazil). Space sharing (which means sharing the space of means of transport or place for warehousing) can be used at various stages of delivery and storage. Space sharing is then combined with the consolidation of shipments. Consolidation can take place in consolidation centers, warehouses, or vehicles. Finally, connecting couriers with shipments is done via mobile apps. Local couriers deliver shipments based on the data received from the app, planning the whole route for the parcel together with proposing crowd members (service providers), waiting times (while switching between them), and travel time with the estimated time of reaching the destination. This occurs in real time. Moreover, the crowd member providing the service may consent to be tracked by the customer or give the details about the Whatsapp or mobile number. Not popular but highly successful is assessing the service providers by customers and giving them badges according to their score and number of provided services. It impacts the customer choice and also the price of the service.

Finally, successful CL solutions provide details about the processes, the whole transaction history and proposes solutions for the identified bottlenecks, even sometimes proposing alternative means of transport or routes and crowd members with the highest scores among the customers. Improving the quality of shipment delivery is now one of the main determinants of success in freight transportation. Delivery quality solutions include door-to-door transportation, as in the case of Flash Express (Thailand), and last-mile solutions using different types of vehicles, as in the case of Delhivery (India) or Bringg (Israel). For customers, a fast delivery time is essential, so many startups opt for a delivery guarantee within a certain period, maybe the next day, an hour, a few hours or less than an hour, as in the case of Darkstore (USA), DroppX (Finland), Tyltgo (Canada) and WareIQ (India). In addition, micro-fulfilment centers can provide additional value in conjunction with shipment consolidation. Urban consolidation centers (UCC) are currently being implemented, but there is a lack of this occurring on a large scale. In the analyzed companies, such a solution is proposed by Darkstore and Fabric (USA).

CL solutions also have some weaknesses, which may include:

1. formal problems in communication between supplier and customer and delays resulting from the supplier's unawareness on the spot [Alharbi et al. 2022].
2. issues related to trust in the service and the supplier in general. Service provision requires submitting sensitive data that can be used improperly [Bortolini et al. 2022, Cieplińska and Szmelter-Jarosz 2020].
3. standardization of the service. Nonqualified personnel may provide CL solutions [Bin et al. 2021, Carbone et al. 2017]. The quality of the service may also be lowered by inadequate technical infrastructure, including a lack of security for mobile applications [Buldeo Rai et al. 2017, Cieplińska and Szmelter-Jarosz 2020].

Poor actor involvement may contribute to accumulating the above problems and the consequent failure to implement a solution. In addition, the security of sensitive data and a sense of trust in providers influence whether an individual will use a CL solution. Therefore, investing in developing networks and IT systems is necessary to support CL functioning.

DISCUSSION

According to the theory of innovation, innovation is not just an idea. The developing market for this type of service can now be observed. Some experts can also assess the development phase of this market as the initial one. Consequently, it cannot be stated that CL is not an innovation. CL is part of the so-called process innovations identified both by Schumpeter [Schumpeter 1934, Schumpeter 1942] and other researchers [Carbone et al. 2017, Buldeo et. al. 2017, Li et. al. 2019] and included in the Oslo Manual [OECD/Eurostat 2018]. The location of CL in the innovation theory is an attempt to identify a relatively new phenomenon in various combinations of processes and opportunities for the emergence of new markets in the economy in the 21st century.

According to various definitions of innovation, CL is a new idea on the logistics services market. It is also a qualitatively different service from the traditional ones provided by companies. Considering the price reduction strategy, CL meets the requirements of innovation as an example of an already existing service, but at lower prices resulting from a new approach to business. In other words, CL successfully exploits new ideas [Porter 1990]. According to the Olso Manual, CL is a new, improved process used to deliver the service (process innovation). According to Schumpeter, CL will introduce a "new organization of the industry".

This study's added value is the focus on identifying why some CL initiatives have failed to optimize L-MD and some have provided value for the customer, allowing them to be assessed as successful. By understanding the reasons for past failures, researchers and practitioners can develop more effective solutions to optimize L-MD using CL.

There are several reasons why some CL solutions did not survive on the market:

1. Lack of user adoption: CL solutions rely on a critical mass of users to be successful. If there are not enough users using the platform, the network effects that are necessary for the platform to function will not materialize.
2. Technical limitations: CL solutions often require sophisticated algorithms and technical infrastructure to operate effectively. If these technical components are not developed or maintained properly, it can lead to poor performance, reduced reliability, and negative user experiences. This can result in user churn and damage to the platform's reputation.
3. Regulatory challenges: CL solutions can face regulatory challenges that prevent them from operating effectively. These challenges can lead to a lack of supply and demand, and ultimately, failure of the platform.
4. Financial challenges: CL solutions can be expensive to develop and maintain and may require significant capital investment. Additionally, competition in the market can lead to price wars and reduced margins, further exacerbating financial challenges.
5. Lack of differentiation: CL solutions can face challenges in differentiating themselves from competitors in the market. If many platforms offer similar services, users may not see a compelling reason to use one platform. This can result in a lack of user adoption and ultimately, failure of the platform.

Overall, the success of CL solutions depends on a complex set of factors, including user adoption, technical capabilities, regulatory environment, financial sustainability, and differentiation. Addressing these challenges requires a comprehensive approach that considers each platform's unique characteristics and the broader logistics ecosystem in which it operates.

CL solutions have seen the most success in densely populated urban areas, particularly in regions with high internet and smartphone penetration rates. Some of the most successful regions for CL solutions include the US, Europe, and parts of Asia. One reason for this success is that urban areas often have high traffic congestion, making traditional delivery methods inefficient and slow. CL solutions, which rely on a network of individuals and vehicles, can be more agile and flexible in navigating traffic and delivering packages. This can lead to faster delivery times, reduced costs, and improved customer satisfaction.

Another reason for success in these regions is the availability of a large pool of potential users and service providers. Densely populated urban areas often have high numbers of potential users and service providers, which can help create the network effects necessary for CL solutions to function effectively. Additionally, the high internet and smartphone penetration levels in these regions make it easier for users to access and use these platforms.

Finally, many successful CL solutions in these regions have addressed user adoption challenges, technical capabilities, regulatory environment, financial sustainability, and differentiation that can lead to failure. By developing effective marketing strategies, investing in technical infrastructure, navigating regulatory challenges, ensuring financial sustainability, and differentiating themselves from competitors, these platforms have gained traction and established themselves as viable alternatives to traditional logistics solutions.

Overall, the success of CL solutions in specific regions is a complex interplay of factors, including population density, infrastructure, regulatory environment, and platform-specific characteristics. Understanding these factors is crucial for developing effective CL solutions that can thrive in specific regions and markets.

CONCLUSION

In conclusion, CL has emerged as a promising alternative to traditional logistics solutions, offering greater agility, flexibility, and cost-effectiveness. Furthermore, successful CL platforms have established themselves in densely populated urban areas, particularly in regions with high internet and smartphone penetration. Therefore, understanding these factors is crucial for developing effective CL solutions that can thrive in specific regions and markets and for creating a sustainable future for the logistics industry as a whole.

On the one hand, CL is undoubtedly different from traditional logistics models, as it relies on a decentralized and flexible network of individuals rather than a centralized logistics provider. Moreover, CL can potentially disrupt the existing logistics industry by offering a more cost-effective and environmentally friendly alternative. On the other hand, CL can also be seen as continuing the trend towards the sharing economy and using P2P (peer-to-peer) platforms to connect individuals with goods and services. In this sense, CL may not be a fundamentally new idea but rather a new application of existing technologies and business models. However, it should still be considered an innovation–a process innovation.

Even if this study provides some valuable insights, it still has a few limitations:

Lack of data: The study may have been limited by a lack of data on CL solutions, particularly concerning their performance and impact on the logistics industry.

Changing market conditions: The study was conducted during a specific period and may not have accounted for changes in market conditions that could affect the performance and sustainability of crowd logistics solutions over time, especially after January 2023 when the solutions were reviewed.

Overall, these limitations highlight the need for further research on CL solutions and their limitations, particularly as the logistics industry continues to evolve and adapt to changing market conditions and technological innovations.

In conclusion, CL is a relatively new phenomenon, but it has already attracted significant attention from researchers and practitioners. The existing literature suggests that CL has several advantages over traditional logistics models, including lower costs, increased flexibility, and reduced environmental impact. However, it also faces several challenges, such as the lack of control over the delivery process. Whether CL represents an innovation is a matter of debate, but it is clear that it can disrupt the existing logistics industry and offer a more efficient and sustainable alternative. Further research is needed to fully understand the potential of CL and its implications for the logistics industry.

There are several potential future research directions on CL, including:

1. Sustainability: Research could focus on the environmental impact of CL solutions and ways to make them more sustainable, such as reducing emissions and optimizing delivery routes.
2. Adoption and usage: Research could explore the factors that influence user adoption and usage of CL platforms, and how these factors vary across different regions and industries.
3. Technology: Research could examine the role of technology in the development and adoption of crowd logistics solutions, including the use of AI, blockchain, and other emerging technologies.

4. Regulation: Research could investigate the regulatory environment for CL solutions, including issues related to liability, data privacy, and worker protections.
5. Collaboration: Research could explore ways to promote collaboration and coordination among different CL platforms and stakeholders, including logistics companies, retailers, and customers.

These research directions highlight the need for a multidisciplinary approach to understanding and developing effective CL solutions. By addressing these issues, future research can help to create a more sustainable, efficient, and equitable logistics industry.

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The raw data for the results can be found here: https://doi.org/10.6084/m9.figshare.22785353.v1

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ORIGINAL PAPER

ON THE USE OF MACHINE LEARNING TECHNIQUES AND DISCRETE CHOICE MODELS IN MODE CHOICE ANALYSIS

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ABSTRACT. Background: The mode choice stage is a critical aspect that transportation experts rely on to develop a robust transportation system for a particular region. Various techniques are utilized to model mode choice behavior, including Discrete Choice Models (DCMs) and Machine Learning (ML) techniques. However, existing reviews typically focus on either DCMs or ML techniques, and reviews that cover both categories often concentrate on one category while merely mentioning some techniques from the other. This paper aims to address this gap by examining the principal DCMs and ML techniques published over the past four years, differentiating between models based on the granularity level, namely aggregate and disaggregate models. Additionally, a comprehensive discussion is conducted on the accuracy of the different models used in the reviewed articles.

Methods: This paper provides a thorough and enhanced analysis of travel mode choice models and analysis techniques used in articles published on "ScienceDirect" from 2020 to 2023. To ensure a comprehensive coverage of the subject, a meticulous search strategy was employed, utilizing targeted keywords. As a result, a total of 38 articles were carefully selected for detailed examination and analysis.

Results: The findings of this study highlight the suitability of different modeling approaches for varying levels of analysis. Discrete Choice Models demonstrate effectiveness in aggregate-level analyses, whereas Machine Learning Techniques prove more appropriate for disaggregate-level analyses. Moreover, the study suggests that employing hybrid models can potentially yield a promising solution to attain enhanced prediction accuracy without compromising interpretability.

Conclusions: The examination of selected articles revealed several key points. Firstly, there is a concentration of studies on travel mode choice in European countries, China, and the USA, indicating a need for more research in developing countries. Secondly, the reviewed articles often lack in-depth analysis of individual behavior and fail to consider external factors like weather or seasons when employing disaggregate models. Thus, future studies should leverage technological advancements and explore new factors influencing mode choice behavior. Additionally, there is a need for further research on hybrid models that combine Discrete Choice Models (DCMs) with Machine Learning (ML) techniques or deep learning approaches. This research can provide guidance for practitioners unfamiliar with these methods and aid in the design of effective transportation policies. Lastly, considering the variety of models available, it is crucial to understand the extent to which these models can be generalized to different contexts, emphasizing the importance of studying model applicability and generalizability in diverse settings.

Keywords: travel mode choice, machine learning, discrete choice model, hybrid models

INTRODUCTION

The transportation industry has undergone rapid development in recent years, providing cities with a variety of modes of transportation including trains, cars, buses, and two-wheel vehicles. This has resulted in a multitude of options for individuals to choose from when deciding how to travel. To ensure the safe, efficient, and environmentally friendly movement of people and goods, it is necessary to understand the characteristics that consumers consider when selecting their preferred mode of transportation, and how they prioritize these factors in order to design a well-optimized transportation system.

To address this challenge, researchers have employed numerous techniques, including the Discrete Choice Models (DCMs) family introduced by Ben-Akiva and Lerman [1985].

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These models attempt to predict travel demand and individual behaviors when presented with various alternatives and have long been the main tools for predicting individual choice behavior. However, with the development of computers, new techniques have emerged, such as Machine Learning (ML) classifiers that have taken the prediction of travel mode choice to new heights.

Several studies have compared ML techniques and DCMs [Xie et al., 2003; Zhang and Xie, 2008; Wang and Ross, 2018; Cheng et al., 2019; Wang et al., 2020]. They have found that ML techniques generally outperform discrete choice models in terms of robustness and accuracy, but they may lack interpretability [Mohammadian and Miller, 2002; Wang et al., 2020]. The advantages and disadvantages of the two different models' categories have led researchers to try to combine both, creating new hybrid models [Wong and Farooq, 2021] or at least using different models from the two categories to benchmark results or reach the accuracy of ML techniques while ensuring the interpretability of DCMs [Wang et al., 2020].

In fact, most of the existing reviews mainly focus on discrete choice models [Barff et al.,1982; Jing et al., 2018]. Ratrout et al., [2014] and Sekhar [2014] enumerate artificial intelligence approaches as well as discrete choice models, with a focus on artificial neural network and fuzzy logic approaches, while not covering ML techniques. Hillel et al., [2021], on the other hand, deal with ML techniques and artificial intelligence approaches used for passenger choice modelling but limits the DCMs only to the logit-based models. Additionally, neither of the previous reviews distinguishes between the models based on the granularity level, namely aggregate versus disaggregate, even though predicting the behavior of one individual or a group of people differs in many ways.

This review aims to comprehensively cover the various Discrete Choice Models (DCMs) and Machine Learning (ML) techniques used for individual and aggregate-level travel mode choice modeling. Specifically, it focuses on studies published within the last four years and examines the dataset collection techniques, granularity levels, and model types used. The second section outlines the methodology used for identifying relevant studies and the data extraction process. In the third section, a concise overview of existing data collection techniques is provided, followed by an enumeration of DCMs and ML techniques used for travel mode choice modeling. The fourth section presents the findings, and the fifth section discusses the accuracy of the reviewed models. Finally, the paper concludes by identifying research trends for passenger choice modeling in each category.

METHODOLOGY

Searching Approach

The study was based on peer reviewed journal articles published in "Science direct" over the four past years. This database includes a high number of publications, and it is one of the most used.

Due to the purpose of covering both the traditional models (DCMs) and the new ones (ML techniques) while trying to identify the relevance of every category for researchers, the following keywords were selected: *Mode choice, travel mode, discrete choice, machine learning, neural network, and fuzzy logic.*

In order to select papers that mainly discuss applications of both DCMs and ML techniques in travel choice behavior, the previous terms were combined as follows:

Science direct: (TITLE-ABS-Key: ("mode choice" OR "travel mode") AND ("machine learning" OR "neural network" OR "discrete choice "OR "fuzzy logic")).

The search resulted in 94 articles, out of which 56 were excluded after analysis. Ten of the excluded articles were conference papers, while 28 were found to be irrelevant to our study. Additionally, 16 articles used DCMs or ML techniques for topics related to transportation other than travel choice behavior. One article focused on a literature review regarding the value of time concept applied to freight transportation, and another article discussed social sciences. As a result, 38 articles were included in the final analysis, and are listed in Table 1.

Table 1. Selected articles for review

Id.	Paper	Id.	Paper
A1	Chang et al., [2020]	A20	Ali et al., [2022]
A2	Li et al., [2020]	A21	Alta de waal and Joubert [2022]
A3	Nguyen and Armoogum [2020]	A22	Bari et al., [2022]
A4	Sanko [2020]	A23	Feng et al., [2022]
A5	Ton et al., [2020]	A24	Gupta et al., [2022]
A6	Wang et al., [2020]	A25	Harz and Sommer [2022]
A7	Yu [2020]	A26	Kapitza [2022]
A8	Zhoa et al., [2020]	A27	Kashifi et al., [2022]
A9	Andani et al., [2021]	A28	Okami et al., [2022]
A10	Jochem et al., [2021]	A29	Saiyad et al., [2022]
A11	L. Yang [2021]	A30	Salas et al., [2022]
A12	Ilahi et al., [2021]	A31	Tao and Nass [2022]
A13	Mo et al., [2021]	A32	Varghese et al., [2022]
A14	Nasrin and Bunker [2021]	A33	Wu et al., [2022]
A15	Song et al., [2021]	A34	Guo et al., [2023]
A16	Sun and Wandelt [2021]	A35	Hamadneh and jaber [2023]
A17	Tu et al., [2021]	A36	Parmar et al., [2023]
A18	Wong and Farooq [2021]	A37	Xia et al., [2023]
A19	Yang et al., [2021]	A38	Zhang et al., [2023]

Data Extraction

After identifying the main articles for the review, we extracted relevant data based on predetermined criteria. Our methodology involved setting up filters for data extraction based on two primary criteria: the type of data collection technique used and the level of aggregation considered. The first category of data collection techniques was further subdivided into three techniques: GPS-based data, the interviewing method, and the web-based interviewing method. The second category was divided into three subcategories: DCMs, ML techniques, and other models. The "other models" category included several methods. Figure 1 illustrates the chosen data extraction process.

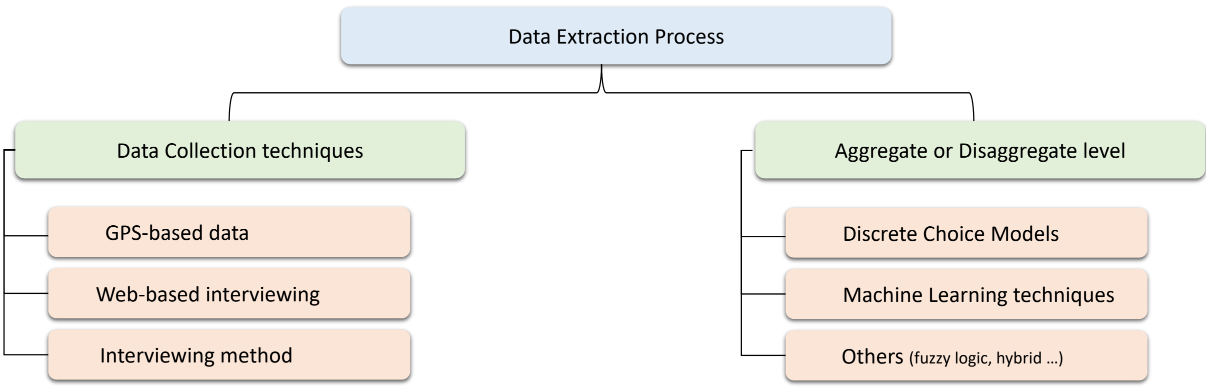

Fig. 1. Data extraction process

MODE CHOICE MODELS AND TECHNIQUES

Data Collection Techniques

As we have previously discussed, Discrete Choice Models (DCMs) and Machine Learning (ML) techniques are commonly used to model either the choice behavior of individuals (disaggregate model) or the choice behavior of a group (aggregate model). However, to obtain accurate outputs from these models, high-quality inputs are required. In this case, the inputs consist of datasets containing information about individuals' preferences for different modes of transportation. To collect this data, various methods are available, each with its own advantages and limitations. Advanced techniques like GPS-based methods or online surveys are commonly used in developed countries, while paper and pencil interviews (Classic interviewing method) are more common in developing countries due to cost constraints and limited internet access.

Regardless of the specific method used, data collection techniques can be broadly classified into three categories, each with its advantages and disadvantages.

GPS-based data (GPS): This category englobes all the techniques that are based on determining the position of the items. The tools usually used could be smartphones, dataloggers, smart cards, etc.

Interviewing method (IM): This technique is based on conducting and filling a preference survey (Stated-SP-or Revealed one-RP) administered to individuals.

Web-based interviewing method (WIM): This technique is simply based on a web questionnaire administered through websites and social networks. This technique could be especially useful when several exogenous restrictions are taking place due to extraordinary contexts or long periods of crisis, such as the pandemic episodes.

Discrete Choice Models

Discrete choice models are a class of statistical models used to analyze and predict the choices made by individuals among a set of discrete alternatives, such as choosing a mode of transportation, a brand of product, or a type of housing. These models assume that individuals choose the alternative that provides the highest utility function, based on the characteristics or attributes of each alternative and their personal preferences. Discrete choice models are widely used in transportation planning and other fields where choice behavior is important. They can provide valuable insights into the factors that influence individual choices and help predict the outcomes of policy interventions. The main types of discrete choice models are multinomial logit, multinomial probit, mixed logit, and nested logit, alongside other more advanced models (see Figure 2).

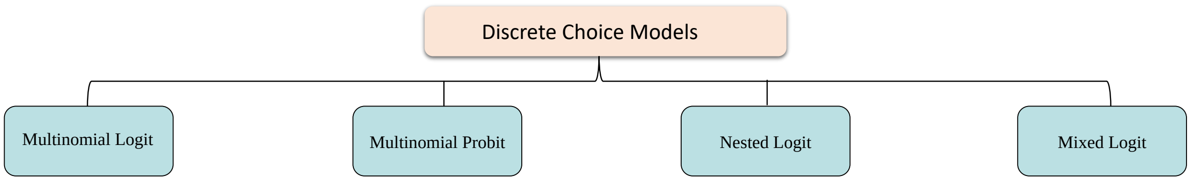

Fig. 2. Discrete Choice Models

Multinomial logit: The multinomial logit is used when the dependent variable is a categorical variable with more than two categories. It is a generalization of the binary logit model, which is used when the dependent variable has only two categories. In the multinomial logit model, the dependent variable is assumed to be drawn from a multinomial distribution, which is a generalization of the binomial distribution to more than two categories. The model estimates the probability of each category by using a logistic function, which is a sigmoid curve that maps any real-valued number to a value between 0 and 1. The multinomial logit model is often used in marketing research and other fields where researchers are interested in predicting which of several alternatives a respondent will choose. It is also used in political science and economics to predict voting behavior and consumer choice, respectively.

Multinomial probit: The multinomial probit model is a type of regression model that is used when the dependent variable is a categorical variable with more than two categories. It is similar to the multinomial logit model, but it assumes that the dependent variable is drawn from a normal distribution instead of a multinomial distribution. The multinomial probit model estimates the probability of each category by using a probit function, which is a cumulative distribution function that maps any real-valued number to a value between 0 and 1. The probit function is the inverse of the standard normal distribution function, and it is used to calculate the probability that a normally distributed random variable will fall below a given threshold. The multinomial probit model is often used in marketing research and other fields where researchers are interested in predicting which of several alternatives a respondent will choose. It is also used in political science and economics to predict voting behavior and consumer choice, respectively.

Mixed logit: The mixed logit model is an extension of the multinomial logit model that allows for more flexibility in modeling the choice behavior of individuals. It is used when the dependent variable is a categorical variable with more than two categories and the independent variables include both continuous and categorical variables. The mixed logit model accounts for unobserved heterogeneity in the data by including random effects. These random effects allow for the modeling of individual-level differences in preferences and decision-making processes that are not captured by the observed independent variables.

Nested logit: The nested logit model is used to analyze data in which the dependent variable is a categorical variable with more than two categories and there is a hierarchical structure to the choices being made. It is a generalization of the multinomial logit model, which is used when there is no nesting in the data. In the nested logit model, the choices are divided into disjoint groups called nests, and the choice within each nest is modeled using a logistic function, which is a sigmoid curve that maps any real-valued number to a value between 0 and 1. The probability of choosing a particular nest is then modeled using a second logistic function. The nested logit model is useful for modeling data in which the choices being made are not independent, such as when there is a hierarchical structure to the choices or when the choices are correlated.

Machine Learning Techniques

The use of machine learning techniques in modeling travel mode choice behavior is becoming increasingly popular. One approach involves using these techniques to estimate the parameters of the utility function. In this approach, a machine learning model is trained on a dataset containing observations of individual choices and relevant explanatory variables. The machine learning algorithm then adjusts the parameters of the utility function to minimize the difference between the predicted and observed choices in the dataset. Another approach involves using machine learning to develop more complex models that incorporate multiple utility functions or allow for non-linear relationships between variables. For instance, neural networks can estimate the utility function for each alternative separately and then combine them to predict the final choice. Overall, machine learning techniques offer a flexible and powerful approach to estimating utility functions in discrete choice models, which can enhance the accuracy and robustness of choice predictions. In Figure 3, we have illustrated the commonly used machine learning techniques for modeling travel mode choice behavior.

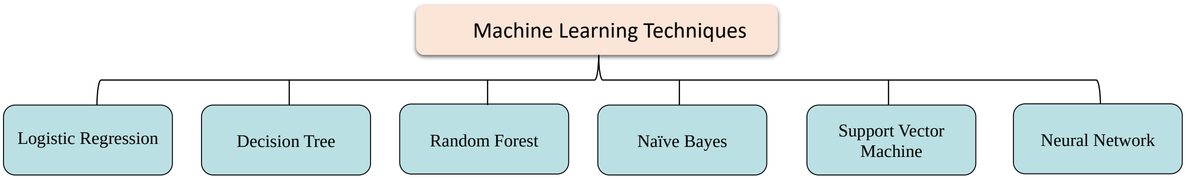

Fig. 3. Machine Learning Techniques for Travel Mode Choice Behavior Modelling

Decision Tree (DT): A decision tree is a tree-like model used for classification and regression tasks. It is a supervised learning algorithm that can be used to predict a target variable by learning decision rules inferred from features of the data. The tree is constructed by making decisions based on the features of the data, starting at the root node and working down the tree until a decision or prediction is made at a leaf node. The decisions made at each node are based on the values of the features and the target variable, and the tree is trained using labeled data. Once trained, the decision tree can be used to make predictions about new, unseen data by following the decision rules learned during training.

Random Forest (RF): A random forest is an ensemble machine learning algorithm used for classification and regression. It consists of a collection of decision trees, trained on randomly selected subsets of the training data, with the goal of reducing the variance and improving the predictive accuracy of the model. During the training process, each tree in the random forest makes a prediction based on the features of the input data, and the final prediction is made by averaging the predictions of all the trees. The random forest algorithm is a popular choice for many machine learning tasks because it is easy to implement, can handle a large number of features, and generally produces good performance on a wide range of tasks.

Logistic Regression (LR): Logistic regression is a statistical model that is used for binary classification, i.e., to predict a binary outcome (such as success or failure, 0 or 1, etc.) based on one or more predictor variables. It is a linear model that is based on the assumption that the relationship between the dependent variable and the predictors is linear, and that the outcome is a binary variable that follows a logistic distribution. During the training process, the logistic regression model estimates the coefficients of the predictor variables, and these coefficients are used to make predictions about the outcome for new data. Logistic regression is widely used in a variety of applications, including image and speech recognition, natural language processing, and social media analysis.

Naïve Bayes (NB): Naive Bayes is a classification algorithm based on the Bayes theorem, which states that the probability of an event is equal to the prior probability of the event multiplied by the likelihood of the event given some evidence. In the context of classification, the event is the class label, and the evidence is the feature values of the input data. The "naive" part of the algorithm comes from the assumption that all the features are independent of each other, given the class label. This assumption is often unrealistic, but the algorithm works well in practice and is particularly useful when there are many features and the relationships between them are not well understood.

Support Vector Machine (SVM): Support vector machines work by finding a hyperplane in a high-dimensional space that maximally separates the data points of different classes. The hyperplane is chosen in such a way that it has the largest distance (called the margin) to the nearest data points of any class, which are called support vectors. The main advantage of SVMs is that they can handle high-dimensional data and data that is not linearly separable. They do this using the kernel trick, which allows them to map the data into a higher-dimensional space where it becomes linearly separable. In addition, SVMs can give probabilities for classification tasks by using Platt scaling.

Artificial Neural Network (ANN): A neural network is a type of machine learning model inspired by the structure and function of the human brain. It consists of layers of interconnected nodes (also called neurons), which process and transmit information. There are several types of neural networks, including Feedforward Neural Networks (FFNN), Recurrent Neural Networks (RNN), and Convolutional Neural Networks (CNN). Neural networks have been widely used in behavior prediction, such as predicting consumer behavior or travel mode choice. They are able to learn patterns and relationships in data and can make predictions based on these patterns.

RESULTS ANALYSES

The articles selected in this literature review present the characteristics of techniques used for analyzing travel mode choice. In an effort to capture this concept, this section uses evidence from the 38 studies to explore each of the three criterions identified to develop a broader understanding, namely: the level of aggregation considered, the data collection techniques used, and the analyzing techniques employed.

Classification by Level of aggregation

We refer to the level of aggregation as the degree of detail at which the preferences are grouped together or classified. It involves deciding how to categorize the data and the prediction into broader categories or classes for the purpose of analysis. An aggregate model is a type of model that uses summary data to make predictions or draw conclusions about a group of individuals having the same characteristics. In contrast, a disaggregate model is a type of model that uses individual-level data to make predictions or draw conclusions about the behavior or choice of individual actors. The level of aggregation can have an impact on the complexity of the model, as well as the usefulness of the results for different purposes.

Based on the findings presented in Figure 4, it can be observed that out of the total number of articles analyzed, 32 articles used an aggregate model, while only 6 articles employed a disaggregate model. The results suggest that disaggregate models are particularly suited for addressing specific research objectives, such as analyzing travel behavior in response to cost reductions [Li et al., 2020; Bari et al., 2022], identifying travel modes [Nguyen and Armoogum 2020; Yu 2020], or building effective recommendation systems [Sun and Wandelt 2021; Wu et al., 2022].

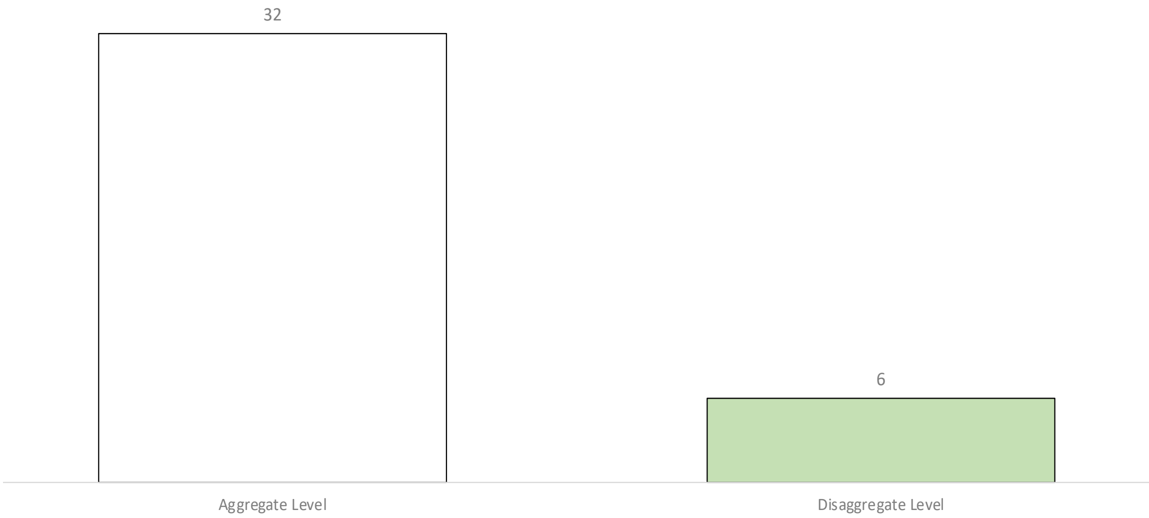

Fig. 4. Paper by level of aggregation

The Relationship Between Data Sources and Levels of Aggregation

Table 2 presents an overview of the data collection methods used in the analyzed studies. The results show that among the studies analyzed, 28 studies used a classic interviewing method, 7 studies used a GPS-based method, and 3 employed a web-based interviewing method. These findings indicate that researchers have used a variety of data collection methods in their studies, with classic interviewing being the most commonly used method and GPS-based and web-based interviewing method being less common but still utilized in some studies.

Table 2. Relationship between the level of aggregation and the data source

	GPS-based data	Interviewing method	Web-based interviewing method
Aggregate Level	A1, A17	A5, A6, A8, A9, A10, A11, A12, A14, A15, A18, A19, A20, A21, A23, A24, A25, A26, A27, A28, A29, A30, A31, A32, A35, A36, A37, A38	A4, A13, A34
Disaggregate Level	A2, A3, A7, A16, A33	A22	
Total	**7**	**28**	**3**

Furthermore, Table 2 highlights the close relationship between the data source and the level of aggregation in mode choice modeling. We can observe that the choice of data source can influence the level of aggregation in several ways. For instance, if the data source is based on group-level data, such as survey responses from a sample of individuals, then the resulting model will likely be an aggregate model that represents the behavior of the group as a whole [Ilahi et al. 2021; L. Yang 2021; Nasrin and Bunker 2021; Harz and Sommer 2022; Hamadneh and Jaber 2023]. This is because group-level data provide information about the overall behavior of a population or sample, rather than the behavior of individual actors within that population. On the other hand, if the data source is based on individual-level data, such as data collected from GPS devices, then the resulting model will likely be a disaggregate model that represents the behavior of individual actors [Li et al., 2020; Nguyen and Armoogum 2020; Yu 2020; Sun and Wandelt 2021]. This is because individual-level data provide information about the unique characteristics and behaviors of each individual, which can be used to predict their individual preferences in terms of mode choice. Therefore, the choice of data source is an important consideration in mode choice modeling, as it can influence the level of aggregation and the accuracy of the resulting model.

The Relationship Between Levels of Aggregation and Analyses techniques

Table 3 provides a summary of the articles reviewed in terms of the type of analyses techniques used for mode choice modeling. It reveals that a similar number of studies utilized Discrete Choice Models (DCMs) and Machine Learning Techniques (ML), with 17 studies utilizing DCMs and 18 studies employing ML. Some studies explored both methods, either to compare their performances [Saiyad et al., 2022] or their interpretability [Zhoa et al., 2020, Salas et al., 2022]. Additionally, the "Others" category encompasses articles that adopted alternative methods, including fuzzy logic [Nguyen and Armoogum 2020], rule-based systems [Zhang et al., 2023], data mining [Chang et al., 2020], or hybrid models [Andani et al., 2021; Wong and Farooq 2021, Gupta et al., 2022, Parmar et al., 2023].

Table 3. Relationship between levels of aggregation and analyses techniques

	Discrete Choice Models	**Machine Learning Techniques**	**Others**
Aggregate Level	A4, A5, A8, A9, A10, A12, A13, A15, A19, A23, A25, A26, A28, A29, A30, A32, A35	A6, A8, A11, A14, A17, A20, A21, A27, A29, A30, A31, A35, A37	A1, A9, A15, A18, A24, A34, A36, A38
Disaggregate Level		A2, A3, A7, A16, A22	A3, A33
Total	**17**	**18**	**10**

The relationship between the levels of aggregation in mode choice and analysis techniques, such as Discrete Choice Models and Machine Learning Techniques, can be complex and dependent on various factors. Nevertheless, we can observe from Table 3 that Discrete Choice Models are used in aggregate-level analyses, while Machine Learning Techniques are more commonly preferred in individual-level analyses. At the aggregate level, Discrete Choice Models typically use aggregate-level data, such as survey responses, to estimate the relative importance of different factors influencing mode choice, such as travel time, cost, and convenience. Examples of Discrete Choice Models used at the aggregate level include multinomial logit, nested logit, and mixed logit models. At the individual level, Machine Learning Techniques often use individual-level data, such as GPS data, to predict the mode choice behavior of individuals. Examples of Machine Learning Techniques used in mode choice analysis include neural networks, decision trees, random forests, and support vector machines.

Overall, the choice of analysis technique depends on the research question, the available data, and the level of aggregation considered. Discrete Choice Models are typically better suited for aggregate-level analyses, while Machine Learning Techniques are more suitable for disaggregate-level analyses. However, there may be cases where a combination of both techniques is necessary to obtain a comprehensive understanding of mode choice behavior.

Figure 5 presents the utilization of different machine learning techniques and discrete choice models in the analyzed studies. It reveals that under the Machine Learning Techniques category, the Random Forest/Decision Trees (RF/DT) and Neural Networks (NN) were the most frequently employed techniques, appearing in 11 and 10 studies respectively. Support Vector Machines (SVM) and Naive Bayes (NB) were employed in 3 studies each, and Logistic Regression (LR) was utilized in 2 studies, indicating their relatively less frequent usage. Turning to the Discrete Choice Models category, the figure shows that the Multinomial Logit (MNL) model was the most commonly employed, appearing in 14 studies. The Mixed Logit (ML) model was utilized in 3 studies, while the Nested Logit (NL) and Mixed Logit (MNP) models were employed in 2 and 1 study, respectively.

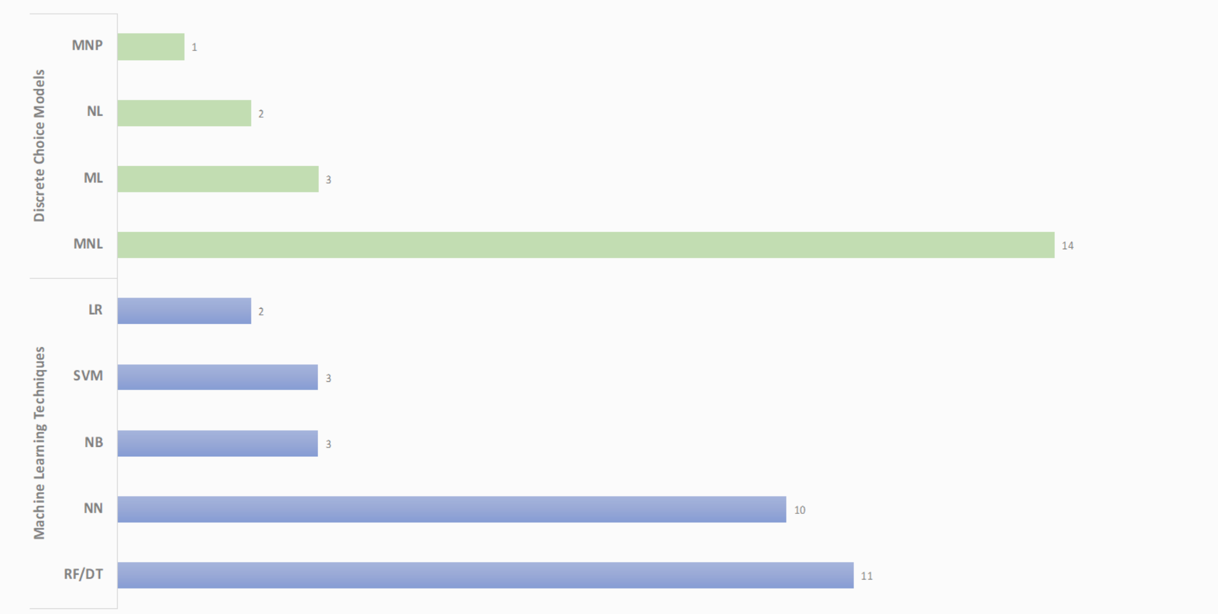

Fig. 5. DCMs and ML models in the selected articles

Figure 5 highlights the prevalence of Random Forest/Decision Trees and Multinomial Logit models in their respective categories, indicating their popularity among researchers in mode choice modeling. The usage of Neural Networks also demonstrates the growing interest in applying machine learning techniques to this field. These findings provide valuable insights for researchers and practitioners seeking to understand the techniques employed in mode choice modeling and the distribution of their usage across different models.

Models Performance

In this section we discuss the performance of the adopted models in the selected articles by comparing the accuracies of the Discrete Choice Models, Machine Learning Techniques, and the hybrid models for each granularity category, namely, the aggregate and disaggregate ones. Six articles based their study on disaggregate models, but only four of them computed the accuracy of their models and compared them with other models: [Li et al., 2020, Nguyen and Armoogum 2020, Yu 2020, Wu et al., 2022]. Secondly, 13 articles used aggregate models; 9 of them based their evaluation on the accuracy criteria: [Wang et al., 2020; Zhoa et al., 2020; L. Yang 2021; Ali et al., 2022; Kashifi et al., 2022; Saiyad et al., 2022; Salas et al., 2022, Xia et al., 2023]. Tables 4 and 5 show the minimum, average, and maximum accuracies (Acc) of the different techniques used in these studies.

Table 4. Accuracies of disaggregate models

Models	Min Acc	Average Acc	Max Acc
Machine Learning	86,7%	89,4%	92%
Hybrid models	91,5%	92,75%	94%
Discrete Choice Models	-	-	-

Table 5. Accuracies of aggregate models

Models	Min Acc	Average Acc	Max Acc
Machine Learning	61%	73,4%	86,3%
Discrete Choice Models	54,2%	62,01%	72%
Hybrid models	63,62%	79,2%	89,87%

Table 5 shows that Machine Learning (ML) techniques outperform Discrete Choice Models (DCMs) in terms of accuracy at the aggregate level. However, it is noteworthy that several studies in this review still opted for DCMs instead of ML techniques, as indicated in Table 3. The reasons behind this choice can be explained as follows: (i) Objectives: ML techniques primarily focus on making predictions, whereas DCMs are not only used for prediction but also for studying the causal factors that influence mode choice behavior. DCMs provide insights into the underlying relationships and factors affecting mode choice, in addition to predictive capabilities. (ii) Interpretability: DCMs offer greater interpretability compared to ML techniques. The meaning of variables and the steps involved in DCMs are relatively clear, making it easier to understand and interpret the results. On the other hand, the interpretability of ML models, especially complex ones like neural networks, can be challenging. The inner workings and meaning of different layers in neural networks may not be readily transparent. (iii) Generalization: DCMs are generally more suited for generalization beyond the specific study. ML techniques, if not properly controlled for overfitting, may suffer from limited generalizability. Overfitting occurs when the model becomes too specific to the training data, leading to poor performance on new unseen data. In contrast, DCMs are designed to capture general patterns and trends in mode choice behavior. In summary, while ML techniques may outperform DCMs in terms of accuracy at the aggregate level, the choice of DCMs in many studies can be attributed to their focus on causal analysis, interpretability, and generalizability.

Gao et al., [2021] proposed a solution to the generalization issue of Neural Networks by developing an extrapolation-enhanced model with knowledge-based decision-making theory. The model was trained on one dataset and extrapolated on two different datasets, giving satisfying results. Hybrid models that combine different techniques could represent the middle ground by acquiring both higher accuracy and maintaining decent interpretability. Li et al., [2020] developed such a hybrid model by combining the generative adversarial model and the convolutional neural network (CNN). The resulting model was compared to other ML techniques, including Random Forest (RF) and Support Vector Machine (SVM), and achieved an accuracy of 86.70%. Nguyen and Armoogum [2020] employed a combination of Random Forest (RF) and fuzzy logic in a hierarchical process to detect travel modes from GPS data. This approach achieved an accuracy of 89.10%. By combining different models' categories, higher accuracies were attained compared to using a single technique. In another study, Wang et al. [2020] developed a novel hybrid model by integrating the utility function with a deep neural network. This hybrid model was then compared to two discrete choice models (multinomial logit and nested logit) and five machine learning techniques (logistic regression, support vector machine, Naïve Bayesian, decision tree, and k-nearest neighbors). The findings revealed that the hybrid model outperformed all the other techniques, with a mean accuracy of 66.30%. These studies demonstrate the benefits of combining different techniques in a hybrid model.

CONCLUSION

This paper presents a comprehensive review of travel mode choice models utilized in articles published within the last four years. A systematic search strategy, employing targeted keywords, was employed resulting in the selection of 38 articles for analysis. A rigorous data extraction process was then applied to these articles, examining the data collection techniques employed, determining whether the models were aggregate or disaggregate, and classifying them into relevant categories, primarily Discrete Choice Models (DCMs) or Machine Learning (ML) models.

The findings reveal that among the selected articles, 32 utilized aggregate models, while the remaining 6 opted for disaggregate models. Additionally, a comparable number of studies employed Discrete Choice Models and Machine Learning Techniques, with some adopting alternative methods. Notably, Discrete Choice Models were predominantly used for aggregate-level analyses, whereas Machine Learning Techniques were more commonly applied in disaggregate-level analyses. A critical discussion on the accuracy of the models utilized in the reviewed articles is presented, suggesting that hybrid models may offer a promising solution for achieving higher prediction accuracy while maintaining interpretability. Furthermore, an examination of the selected articles revealed a concentration of studies in European countries, China, and the USA, highlighting the need for more research in developing countries. Moreover, it is observed that the disaggregate models used in the reviewed articles often lack in-depth analysis of individual behavior and fail to consider external factors such as weather or seasons. Therefore, future studies should leverage technological advancements and explore new factors that influence individual mode choice behavior. Additionally, there is a need for further research on the strengths and potential of hybrid models combining DCMs with ML techniques or deep learning techniques to provide clear guidance for practitioners unfamiliar with these methods, thereby facilitating the design of well-suited transportation policies. Lastly, considering the variety of models available, an important question arises regarding the extent to which the models employed in specific studies can be generalized to other contexts. This calls for a deeper understanding of model applicability and generalizability to ensure their effectiveness in diverse settings.

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ORIGINAL PAPER

THE EFFECTS OF USING ARTIFICIAL INTELLIGENCE AND ROBOTICS IN LOGISTICS SERVICE PRODUCTION: AN APPLICATION IN 3PLS AND 4PLS

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ABSTRACT. Background: The purpose of this study is to investigate how artificial intelligence (AI) and robotic awareness, perceived organizational support, and competitive psychological climate approaches relate to turnover intention. In the literature, studies on robotic awareness and turnover intention have been undertaken in a variety of industries. In this respect, this study aims to address the absence in the literature of research on logistics services providers. This study aims to help businesses understand how to retain employees and foster a more inclusive and supportive workplace.

Methods: The study utilizes survey information from 100 senior managers in the operations function of logistics service providers. The outcomes are obtained by modeling structural equations with SmartPLS. Data from the survey were gathered using the snowball sampling technique.

Results: The results of the research reveal the effect of artificial intelligence and robotic awareness on competitive psychological and turnover intention.

Conclusions: The study aims to explore the role of a competitive psychological climate and organizational support in mediating the relationship between AI and robotics awareness and turnover intention. We identify that awareness of AI and robotics has a considerable, favorable effect on the psychological climate of competition and turnover intention. We also find that the competitive psychological atmosphere has a substantial, favorable effect on turnover intention.

In addition, organizational support has been demonstrated to have a substantial, favorable effect on turnover intention. However, it was not possible to identify the mediating role of organizational support and the psychological environment of competition in moderating the association between awareness of AI and robotics and turnover intention. On the basis of the research's findings, suggestions were made.

Keywords: Artificial intelligence, Robotic awareness, Logistics services provider, Cobots

INTRODUCTION

The technological developments humanity has reached today are based on discoveries and inventions throughout history. In particular, the Industrial Revolution in England in the 18th century and its effects caused developments that facilitated people's lives and fundamentally changed social life. In this first period when technology affected human life, steam machines started to be used intensively in industry (Yıldız, 2018). Technological advances since the start of industrialization—paradigm shifts that are now ex-post referred to as "industrial revolutions"—have occurred, for example, in the mechanization-related fields (first industrial revolution, as the term is used), extensive electrical energy use (referred to as the second industrial revolution), and the widespread use of digital (known as the third industrial revolution) (Lasi et al., 2014).

Businesses today feel obligated to evaluate their business models in light of technological developments to reduce costs and ensure an efficient and reliable supply chain, so much so that in the era of Industry 4.0, people have become involved as system designers across the whole manufacturing system, employees, and customers of the goods produced. Robots have

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developed from simple, automated automata to smart systems with versatile features, and newer types of service robots share the same space and tasks as humans, working in both industrial and service sectors (Savela et al., 2018:493). Also, while the developments in the field of technology have caused some professions to disappear entirely or to be seen less frequently, they have led to the birth of some occupations. As robots and other computer-assisted technologies replace tasks that were formerly performed by people, worries about the future of employment and incomes are growing (Acemoglu, Restrepo, 2017). Regarding this, our study is intended to close the significant research gaps in the literature on logistics turnover intention, perceived organizational support, and competitive psychological climate.

First, we investigate how robotic awareness and artificial intelligence contribute to turnover intention. Second, drawing on past research, we examine how perceptions of organizational support and the psychological climate of competition help us understand how robotic awareness and artificial intelligence affect turnover intentions in the logistics profession.

Each section of the essay is organized as follows: In Section II, a concise assessment of the literature is provided on robotic awareness and artificial intelligence, perceived organizational support, the psychological climate of competition, and turnover intention methodologies. In Section III, we describe the study's research methods. In Section IV, the results are presented following the research model and according to how they are discussed in the literature. Finally, the key conclusions are presented in Section V.

THEORETICAL BACKGROUND

AI and robotics awareness and turnover intention

Industry 4.0 is concerned with connecting all machine components through integrated data chains and processes (Tuba et al., 2017). Global machine networks are emphasized in Industry 4.0.—an innovative factory environment that can independently exchange knowledge and control each other. This cyber-physical system enables the intelligent factory to operate autonomously. For example, since a machine will know the production process that needs to be applied to a product, what changes will be made to that product, etc., it is possible to define that product, its configuration, and the route on the production line as a unique object.

The effects of Industry 4.0 on the whole supply chain need to be analyzed, as it is crucial to ensure good cooperation among manufacturers, suppliers, and consumers to improve transparency in all steps, from the moment the order is placed until the end of the product life cycle (Tjahjono et al., 2017:1175). The Boston Consulting Group, an American company, published a study that identified the following technologies as Industry 4.0 enablers (Baldassarre et al., 2017):

- Advanced Manufacturing Solutions are cooperative, autonomous, and programmable robots that can communicate with people and other robots.
- Augmented Reality is a collection of tools that lets you add details to your feelings.
- Additive Manufacturing describes building objects using additive manufacturing techniques, primarily 3D printing. Additive manufacturing enables enterprises to produce and sell finished products right away on the market or produce individual components that can also add value to products in terms of design, using a variety of fundamental technologies that differ mainly owing to the capacity to employ diverse materials.
- Simulations are essential to minimize faults in products and processes and optimize them.
- Integration of information vertically and horizontally along the whole value chain, from the supplier to the final customer.
- The term "cybersecurity" refers to the requirement to safeguard network security while also protecting computer systems.
- Big Data, which denotes the gathering and processing of vast volumes of data to

enhance goods and manufacturing procedures.
- The Cloud, which symbolizes the requirement to share substantial amounts of data or IT resources, is always accessible over the Internet.
- The Industrial Internet of Things is a collection of technologies and sensors that enable communication between the human and artificial worlds, including the transmission of goods and industrial methods.

The fourth industrial revolution we are currently living in is characterized by the interconnection of sub-components of the production process through the Internet of Things (IoT). Robots are described by the International Organization for Standardization as "programmable devices that can move and carry out tasks in their environment." (Oyekan et al., 2019:41). According to NASA, a robot is a machine that can be used to perform tasks. While some robots can work independently, others always need a person to tell them what to do (Alaiad, Zhou, 2014: 826).

Robots may prove to be a desirable option for humans for material handling in the future due to their error-free operation and sophisticated sensing skills. Robots contribute greatly to production costs, as they can reduce waiting time and speed up automated processes. Robots also offer innovative alternatives to storage processes. They provide flexibility, as they can provide an uninterrupted service. Robotic technology can adapt to complex and changing warehouse environments thanks to self-learning systems. But despite all these advantages, robots are still one of the most expensive solutions in warehouse management (Potkonjak et al., 2011).

Table 1. Cobots and conventional industrial robots are contrasted.

Traditional industrial robots	**Cobots**
Fixed installation	Flexible and portable
Periodic, repeatable tasks; infrequent changes	Frequent task changes; tasks repeated infrequently
On-line and off-line programming	On-line instruction and supported by off-line methods
Traditional programming languages	Easily programmable using graphical user interfaces
Not easy to teach	Easy to teach
Rarely interact with the worker, only when programmed	Frequent interaction with the worker, even force or precision assistance
Workers and robot separated by a fence	Workspace sharing with workers
Cannot interact with people safely	Interacts with people safely
Profitable only with medium to large lot size	Profitable even at small lot level
Small or big and fast	Small and slow
Cannot reduce cost and footprint to justify new applications	Reduce cost and footprint to justify new applications
No requested risk assessment	Requested risk assessment
Usually, 6 axes with last three intersecting in wrist	Usually, 6 and 7 axes with many offsets

Source: Calitz, A. P., Poisat, P., Cullen, M. (2017). The future African workplace: The use of collaborative robots in manufacturing. SA Journal of Human Resource Management, 15(1), 1-11.).

Unlike traditional robot technology, Industry 4.0 robots are expected to move from assistance to cooperation and co-production. These robots are expected to be promoted to the level of colleagues, and it is stated that man and machine will cooperate more intensively in production processes (Berger, 2016). Cobots, also known as collaborative robots, are robotic devices designed to interact physically with people in a shared office. The main advantages of cobots include flexibility in production, less risk, and high performance. Because of cobots, human workers are now assigned to tasks with high added value rather than repetitive or dangerous ones. (Calitz et al., 2017).

Technology support greatly facilitates the organization of work and the circulation of information, reducing production time and allowing products to be of the highest quality to satisfy even the most demanding customers (Grabowska, 2020: 94).

The use of cobots in assembly and production lines will increase worker safety and productivity and expand automation in the production environment. As more cobots are introduced, even more areas of use will be explored (Evjemo, 2020).

AI and robotics can replace repetitive and routine tasks for humans. AI and human collaboration can also increase employee productivity and make business processes more efficient. AI can support human decision-making and work collaboratively. This can reduce employee turnover intentions because their work becomes more efficient and satisfying. On the other hand, integrating AI and robotics into business processes may change the roles, responsibilities, and skills of some employees (Brougham, Haar, 2018).

Where employees find it difficult to adapt to change, it may increase turnover intentions. The impact of AI on turnover intentions is a complex issue that can be influenced by many factors and may differ for each workplace and employee group (Segovia-Perez et al., 2023).

We offer the following hypotheses based on research on AI and robotics awareness and turnover intention.

H1: AI and robotics awareness positively and significantly influences turnover intention.

Perceived organizational support and turnover intention

Turnover intention is defined as an individual's perceived probability of staying or leaving an employing organization (Mendis, 2017). Job dissatisfaction is a key factor in turnover intentions; in fact, if employees experience discontent, they won't be loyal or committed to the company (Thu Suong, 2020).

Perceived organizational support is described as collective perceptions of how much a company values its employees' contributions and cares about their well-being (Aldabbas et al., 2023). Perceived organizational support is a key predictor of turnover intentions and was developed on the premise that employees form opinions about how much a company values their contributions and is concerned about their welfare, based on how they feel the company will reward their hard work and take care of their socio-emotional needs. Increased job satisfaction, performance, dedication, and reduced turnover are outcomes of perceived organizational support (Dawley et al., 2010). Also, employees who reported feeling a lot of organizational support had less workplace stress and recovered more rapidly (Takala, Ramli, 2020).

Employees' perceptions of the organization's ability to value their contributions and concerns are known as perceived organizational support. According to Ardias, an employee's impression of organizational rules, norms, and processes relating to the evaluation of their contributions and welfare is perceived as organizational support (Sumardjo, Supriadi, 2023).

After AI and robots have been implemented on a global scale, it is quite acceptable to question whether they would endanger millions of jobs, resulting in widespread unemployment and job loss. Many studies indicate that as the world becomes more technology-driven, the process of artificial intelligence and robotization could directly displace up to 45% of previously conducted business activities (Li et al., 2019).

High perceived organizational support employees are more likely to demonstrate a strong sense of loyalty and belonging to their employer. Perceived organizational support might thus decrease a worker's intention to leave their job. There is a significant relationship between perceived organizational support and employees' turnover intention. In addition, organizational support leads to a decrease in employees' stress and burnout (Wang, Wang, 2020).

As a result, AI and robotics awareness can have an impact on the behavior of employees at work. Organizations should consider the needs of employees when integrating these technologies into business processes and provide appropriate support and training to help the workforce adapt to technological change. For example, employers investing in AI and robotics technologies to enhance employees' capabilities and using these technologies to reduce employees' workload can increase employees' job satisfaction and therefore reduce turnover intentions. Moreover, a work culture and organizational support that focuses on employee job satisfaction and engagement also play an important role.

Thus, based on the definition of perceived organizational support and turnover intentions, we propose the following hypotheses:

H2: AI and robotics awareness positively and significantly influences perceived organizational support.

H3: Organizational support positively and significantly influences turnover intention.

H4: Organizational support moderates the relationship of AI and robotics awareness with turnover intention.

Competitive psychological climate and turnover intention

The increasing use of artificial intelligence and robotic technologies in the business world may cause employees to face a competitive psychological climate. A competitive psychological climate describes a work environment where employees are encouraged to compete with and outperform one another.

While such a climate can enhance performance, it can also be associated with negative outcomes such as turnover intention.

The phrase "psychological climate" is frequently used to refer to views of workplace conditions in organizational psychology, wherein an individual's attitudes, personality, conduct, motives, mentality, and fundamental beliefs affect the effectiveness of the company. How employees understand and experience their corporate environment is known as the psychological climate (Hassan et al., 2012). The degree to which employees believe organizational rewards are given based on how they perform in comparison to their peers is referred to as the competitive psychological climate. It is suggested that the intense competition among scientists may lead them to give up their academic jobs (Gim et al., 2015).

On the other hand, one of the stresses at work is modern technology, which has been linked to a host of detrimental employment-related consequences, including high levels of job instability and uncertainty about future career advancement (Li et al., 2019).

Employees may have the desire to abandon their jobs, owing to job insecurity as a result of AI and robotics knowledge. Therefore, employee competitiveness might make workers feel more motivated to keep their jobs. A person who has a competitive spirit may learn more about the most recent technologies being used (Khaliq et al, 2022).

On the other hand, where AI and robotics are combined with a competitive psychological climate, there may be intense pressure and the expectation to perform at a consistently high level. This may increase employee turnover intentions. Turnover intention refers to the idea that an employee intends to leave their current job. Furthermore, the use of artificial intelligence and robotics may lead to the automation of some job tasks and the replacement of human labor. This may cause employees to worry about future job security. Working in such a job may increase turnover intention.

Thus, based on the definition of competitive psychological climate and turnover intention, we propose the following hypotheses:

H5: AI and robotics awareness positively and significantly influences a competitive psychological climate.

H6: Competitive psychological climate positively and significantly influences turnover intention.

H7: Competitive psychological climate moderates the relationship of AI and robotics awareness with turnover intention.

RESEARCH METHOD

Today, businesses increasingly need 'one-stop' service providers. Using and relying on the services of various specialists performing a range of logistics tasks is considered to be characteristic of modern business systems. An enterprise can expand its logistics operations outside the organization by purchasing services under a contract with a third-party logistics (3PL) or Fourth Party Logistics (4PL) service provider (Pavlić Skender et al., 2017). 3PL service providers, which are widely preferred in outsourcing, provide significant benefits, such as cost reductions and service improvements. 3PL is considered the orchestrator of the logistics industry (Zacharia et al., 2011). 4PL is a supply chain Strategic Tactical integrator that combines and manages the resources, capabilities, and technology of service providers to deliver a comprehensive supply chain solution (Cezanne, Saglietto, 2015). The main characteristic of a 4PL service provider is said to be freedom of presence, and its core function is to manage its own and third parties' resources, capabilities, and technologies to deliver a comprehensive supply chain solution (Mehmann et al, 2013). 3PL and 4PL service providers were selected as the main population for this study, as they utilize technology in fulfilling the integrator role. In the first study, a qualitative research method was used on industry databases and on the websites of logistics services providers. The aim of this study is to identify the activities of logistics providers. This study allows us to define 4PL service providers.

The survey data was gathered using the snowball survey method. A non-random sampling method called "snowball sampling" is used to encourage a set of concepts to participate in the study (Taherdoost, 2016). One of the most common non-probability sampling approaches, the snowball sampling methodology, is particularly suitable when the population of interest is challenging to contact and when compiling a list of the population causes difficulties for the researcher (Etikan et al., 2016).

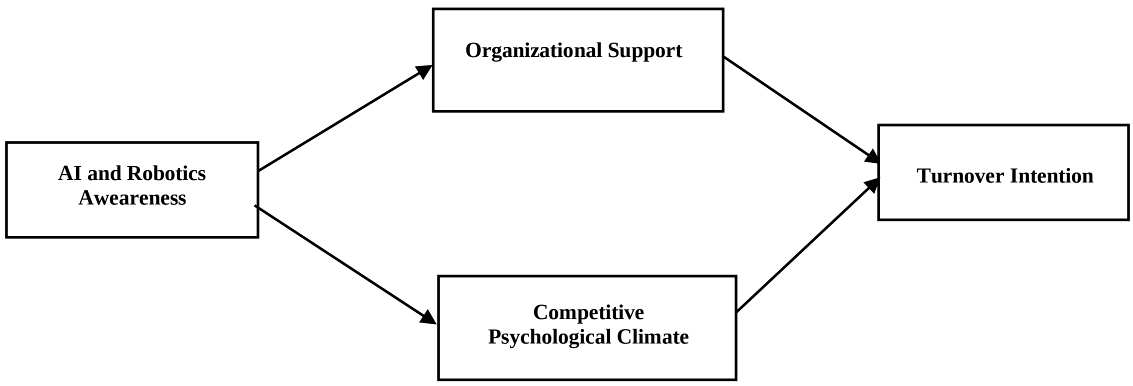

Fig 1. Research Model and Hypotheses

According to the research model, AI and robotics awareness will impact perceived organizational support and competitive psychological climate both directly and indirectly through turnover intention.

RESEARCH MODEL CONSTRUCTIONS

In this study, four main variable groups were used. We invited respondents to the survey's first section to reply to questions on the demographic information of the respondents. The survey's second section used items of dimensions regarding AI and Robotics Awareness. For the third and fourth parts of the survey, we asked the respondents to answer questions about the perceived organizational support and competitive psychological climate of respondents' firms. In the last part of the survey data were collected on turnover intention. Items were taken and modified from Li et al. (2019)'s study to better align them within the context of logistics services providers. The variables of the study are summarized in Table 2.

Table 2. Variables of the study

Demographic information of the respondents
1. Gender
2. Age
3. Education status
4. Work experience
Variables related to AI and Robotics Awareness
5. I think there is a high risk that my job will succumb to automation and my job will be replaced by machines with artificial intelligence.
6. There is a high probability that my job in this organization will be automated.
7. I am very pessimistic about my future in this organization as employees can be replaced by an AI system.
Variables related to perceived organizational support of respondents' firm's present conditions.
8. Our firm strongly considers my personal values and goals when making decisions.
9. Our firm genuinely cares about the well-being of each individual.
10. I can get help immediately if I need it.
11. Small mistakes will be forgiven.
12. Our firm is ready to help me when I need a special favor.
Variables related to competitive psychological climate of respondents' firm's present conditions.
13. I am constantly compared to my colleagues by my supervisor.
14. My reward is determined in comparison to my colleagues.
15. Everyone in this organization wants to be seen as a top performer.
16. My colleagues always evaluate their own performance and compare it with mine.
Variables related to turnover intention
17. I will leave as soon as I find a new job with a higher salary.
18. I think it's time to think seriously about quitting.
19. I'm looking forward to quitting my job.

The question was measured using a Likert-type scale, and the response options ranged from 1 (strongly disagree) to 5 (strongly agree) (see Table 1).

RESULTS

In this section, we present the results of our analysis of the suggested models. In particular, we look at the confirmatory factor analysis and respondent profile, which are described below. Then, we give several managerial standpoint perspectives.

The profile of responder companies

Information about the sampling method and the target participants for a study was provided. The study used convenience sampling, which means that the respondents were selected based on their availability and accessibility rather than through a random sampling method. In this case, the respondents were selected from the member lists of Utikad (Association of International Forwarding and Logistics Service Providers), which currently has 668 members.

The questionnaire was delivered to various individuals within these logistics providers, including chief executive officers, board members, operations managers, sales and marketing managers, and fleet directors of third party and fourth party logistics providers. There were 100 participants involved in this study.

Confirmatory factor analysis

Our PLS-SEM model's indicator reliability, convergent validity, discriminant validity, internal consistency (composite reliability), and indicator reliability are all examined using SmartPLS. When evaluating PLS-SEM measurement models, internal consistency reliability is examined first. The values of Cronbach's alpha of each factor were between 0.815 and 0.906.

It is a different measure that can be interpretable similarly to Cronbach's alpha. Composite reliability values were between 0.871 and 0.941. Thus, internal consistency reliability is said to be provided. Additionally, AVE values should be greater than 0.50, and factor loadings of each indicator (item on the scale) should be higher than 0.60 (Hair et al., 2014). The AVE values were between 0.662 and 0.856, which was considered significant support for convergent validity. The factor loadings were between 0.631 and 0.842. (Table 3).

Table 3. Factor loadings, Cronbach's α, composite reliability, and AVE values of the scale

Item	Factor Loading	Cronbach's α	CR	AVE
AI and Robotics Awareness				
AI1	0,939			
AI2	0,951	*0,905*	*0,941*	*0,842*
AI3	0,859			
Perceived Organizational Support				
OS1	0,828			
OS2	0,819			
OS3	0,874	*0,886*	*0,917*	*0,688*
OS4	0,761			
OS5	0,860			
Competitive Psychological Climate				
PC1	0,882			
PC2	0,846	*0,815*	*0,871*	*0,631*
PC3	0,713			
PC4	0,722			
Turnover Intention				
TI1	0,903			
TI2	0,938	*0,906*	*0,941*	*0,841*
TI3	0,911			

On the basis of the proposed model, a series of multiple regression analyses were used to determine path coefficients. The last findings are shown in Figure 2.

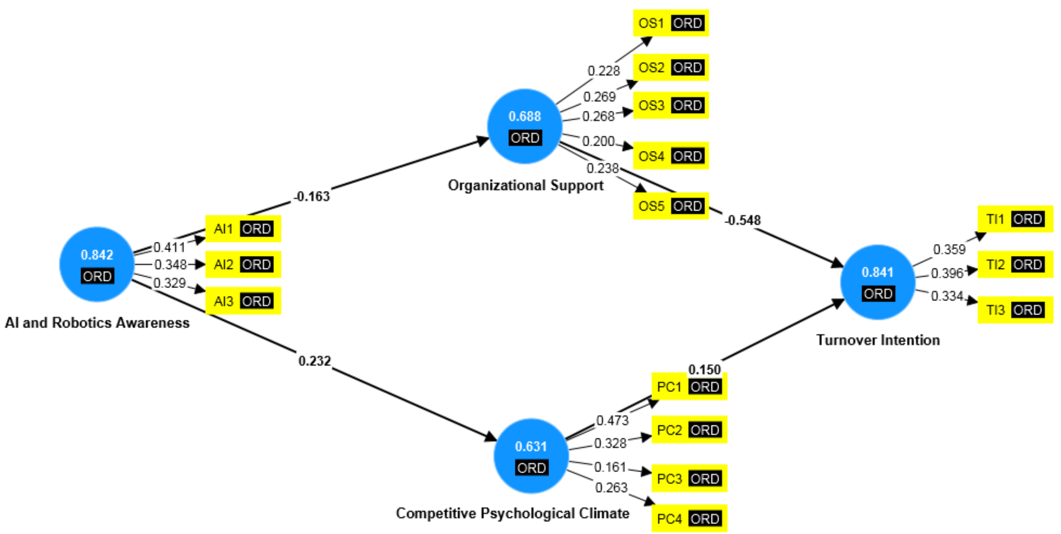

Fig 2. The path model of this study

Henseler et al. (2015) propose the heterotrait–monotrait ratio of correlations (HTMT) as a new approach to assess discriminant validity in variance-based SEM. Authors suggest a threshold of HTMT of 0.90. As seen in Table III, HTMT values are below the threshold value. As can be seen in Table 4, the result indicates that discriminant validity is well established.

Table 4. Heterotrait-monotrait ratio of correlations (HTMTs) for checking discriminant validity

	AI and Robotics Awareness	*Competitive Psychological Climate*	*Organizational Support*	*Turnover Intention*
AI and Robotics Awareness				
Competitive Psychological Climate	0.228			
Organizational Support	0.179	0.519		
Turnover Intention	0.239	0.448	0.687	

Hypothesis testing

The hypotheses are tested using SmartPLS 4, and the findings are shown in Tables 5 and 6. The bootstrapping resampling method was used with 5,000 subsamples to determine the significance of the structural model. The standardized path coefficients and p-values used in the hypothesis testing achieved appropriate results. We find support for H1, H3, H5, and H6 ($p< 0.05$).

Table 5. Significance testing results of the structural model path coefficients for direct effect

Variables	Std. error	t	R^2	P
AI and Robotics Awareness → Competitive Psychological Climate	0,094	2,478	0.673	*0,007*
AI and Robotics Awareness → Organizational Support	0,107	1,524		0,064
AI and Robotics Awareness → Turnover Intention	0,070	1,776		*0,038*
Competitive Psychological Climate → Turnover Intention	0,091	1,647		*0,049*
Organizational Support → Turnover Intention	0,100	5,476	0.270	0,000

We find a significant, positive impact of AI and robotics awareness on competitive psychological climate and turnover intention. We also found a significant, positive impact of competitive psychological climate on turnover intention. Furthermore, a significant, positive impact of organizational support on turnover intention has been found.

The model's predictive power is reflected by the variables' R-squared values (Hair et al., 2014). The effect size of variables can be classified as large (Wetzls et al., 2009) (see Table 5).

Table 6.. Significance testing results of the structural model path coefficients for mediating effect

Variables	Std. error	t	p
AI and Robotics Awareness → Competitive Psychological Climate → Turnover Intention	0,029	1,212	0,113
AI and Robotics Awareness → Organizational Support → Turnover Intention	0,060	1,497	0,067

The analysis's results suggested that AI and Robotics Awareness have not mediated the impact of Competitive Psychological Climate and Organizational Support on the Turnover Intention, not supporting hypotheses H4 and H7 (see Table 6).

CONCLUSIONS

There is growing interest and research in leveraging the natural and unique capabilities of both robots and humans in collaboration. The increasing presence of robots and robotic systems in various industries and sectors does indeed bring about significant advantages in terms of productivity and cost-effectiveness. However, there are valid concerns regarding the potential impact on employment and the broader economy. The findings also have some important implications for managers. Firstly, increased robot employment will lead to unemployment. One argument is that the adoption of robots in the workforce may result in job displacement for human workers. As robots become more capable of performing tasks traditionally done by humans, there is a concern that a significant number of jobs will become obsolete. This can lead to unemployment, especially for workers in industries that heavily rely on manual labor. Moreover, the use of robots may reduce labor costs for businesses. As a result, companies might opt to replace human workers with robots to cut expenses, exacerbating the potential unemployment problem. If a large portion of the workforce remains unemployed, it can have adverse effects on the economy, such as decreased tax revenues, reduced consumer spending, and increased reliance on social welfare programs.

Secondly, adaptation and training will create new opportunities. An alternative perspective acknowledges the potential for job displacement but emphasizes the importance of adapting to new technologies. Advocates of this viewpoint argue that instead of fearing unemployment, efforts should be made to train and reskill the workforce to align with the changing demands of the job market. Training programs can be established to equip workers with the necessary skills to operate and maintain robotic systems, as well as to develop expertise in emerging fields related to robotics and automation. This approach can lead to the creation of new job opportunities in areas such as robotics engineering, programming, and system maintenance.

Additionally, as robots become more prevalent, they can take over hazardous or physically demanding tasks, reducing the risk of workplace accidents and injuries. This shift can lead to safer working environments and improved overall well-being for workers. On the other hand, according to a different view, employees should be trained following the new technology training, new job fields to be opened, and the creation of a new, qualified, and educated working segment in society. Over time, robots being able to perform many tasks that can be dangerous for humans will become common place.

This study supported previous research on the competitive environment by demonstrating that a highly competitive workplace is linked to higher turnover intentions. Additionally, this study demonstrated a favorable relationship between AI and robotics awareness and turnover intention, corroborating other findings.

The majority of earlier research was conceptual, descriptive in form, making recommendations, or concentrated on the behavior of employees in terms of robots and artificial intelligence. The conceptual papers examined significant research topics and outlined a study agenda for the future. They also offered several frameworks for organizational support, turnover intention, turnover awareness, and competitive psychological climate. The few studies that have looked at the connections between the variables included in this study are quite rare. In addition, there is no research examining the relationships of the existing variables in the field of logistics.

We have discovered that awareness of AI and robots has a considerable, favorable effect on the psychological environment of competition and turnover intention. We also discovered that a competitive psychological atmosphere has a large, favorable effect on turnover intention. In addition, organizational support has been shown to have a large, favorable effect on turnover intention.

The study by Gabriel et al. (2014) looked at the connections between turnover intention and a competitive psychological climate. According to the study's findings, the likelihood of turnover is strongly correlated with the competitive psychological climate.

According to Brougham and Haar's research from 2017, moderators should receive greater attention when examining how employees perceive robots and AI in relation to workplace outcomes. In addition to responding to Brougham and Haar's (2017) appeal, the current study adds new, further theoretical insight into how organizational support and AI awareness impact an employee's intention to leave their job. The results of this new study show that turnover intentions and AI awareness are related.

The results of Li et al. (2019)'s study show that when employee behaviors and activities are acknowledged and rewarded by their employer, there is a weakening association between AI awareness and turnover intentions. From a theoretical perspective, it emphasizes the role of a competitive psychological climate and organizational support in mediating the relationship between AI and robotics awareness and turnover intention (Li et al., 2019). However, the mediating effect indicated in this study was not detected. The environmental factors of the country where the research was conducted and the variables related to the sector may be the reason for this.

The reasons for the lack of a mediating effect of organizational support between AI and robotics awareness and turnover intention may be due to various factors such as negative attitudes towards technology, concerns about job security, lack of adequate training and support, emotional commitment, organizational culture, and management attitude and communication. Understanding and addressing these reasons can help organizations adapt to technological transformation and help employees work in harmony with technology.

Environmental factors of a country can include cultural norms, legal frameworks, and economic conditions, among others. These factors can significantly impact the adoption and acceptance of AI and robotics in the workplace, as well as employee attitudes towards them. Additionally, variables related to the sector, such as the nature of the work, the level of automation already present, or the industry's competitiveness, can also influence how AI and robotics awareness relates to turnover intention. However, considering the contextual factors mentioned, it is plausible that the absence of a mediating effect could be attributed to the complex interplay between country-specific and sector-specific factors, which were not adequately accounted for in the study. Future research could explore these factors further to gain a more nuanced understanding of the relationship between AI and robotics awareness, turnover intention, and the mediating role of competitive psychological climate and organizational support.

In conclusion, while the increasing use of robots and robotic systems in the workforce has the potential to disrupt employment patterns, it is essential to adopt a proactive approach. By providing adequate training and support to the workforce, societies can benefit from the advantages offered by robots while mitigating the negative impact on employment. Embracing new technologies can lead to the creation of new job opportunities and a more efficient and safer work environment in the long run.

It is recommended that future studies be tested on different samples and on enterprises with different levels of automation and applied in different cultures.

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ORIGINAL PAPER

FACTORS INFLUENCING THE APPLICATION OF BLOCKCHAIN TECHNOLOGY IN AGRICULTURAL SUPPLY CHAIN MANAGEMENT: SYSTEMATIC LITERATURE REVIEW AND SOCIAL NETWORK ANALYSIS

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ABSTRACT. Background: Blockchain technology, widely recognised as a disruptive innovation, has profound potential to revolutionise agricultural supply chain management. Despite the optimistic outlook associated with its application, the existing exploration and deployment of blockchain in the agricultural sector remains at a relatively rudimentary stage, indicating that this transformative technology has yet to fully realise its inherent potential within this sphere. This study aims to identify the critical factors and explore the relationships among the factors that influence the willingness and efficacy of adoption and implementation of blockchain technology in agricultural supply chain management.

Methods: First, a systematic literature review (SLR) was conducted using VOSviewer software to visualize the status and development tendencies of research in the field of blockchain technology, and core authors in the field were identified. Second, the papers selected through SLR were further screened based on the PRISMA guidelines and discussions with experts to identify the challenges and influencing factors of adopting blockchain technology in the agricultural supply chain. Finally, social network analysis was conducted to identify the key influencing factors and explore the network relationships.

Results: Perceived cost, Establishment of consensus network, and Privacy and security are the critical factors influencing the adoption of blockchain technology in the agricultural supply chain. Policy Support is another key influencing factor. Overall, technological factors dominate the adoption willingness of users.

Conclusions: This study used social network analysis to identify the factors influencing the adoption of blockchain technology in agricultural supply chain management. The study findings will help develop targeted policy measures for blockchain application from the perspective of agriculture practitioners.

Keywords: Blockchain technology, agricultural supply chain management, disruptive technology, social network analysis

INTRODUCTION

In recent years, agricultural supply chain management has become the key factor in the development of modern agriculture. The development of the market economy and the acceleration of economic globalization has led to the formation of a global agricultural supply chain network, and the importance of agricultural supply chain management has become increasingly obvious. However, the agricultural supply chain is a long chain with numerous links and participants, which causes management problems such as poor information communication, inefficient supervision [Zhang et al. 2020], and difficulty maintaining quality and safety standards [Wang et al. 2021]. The current agricultural supply chain network in China is "scattered, disorderly, weak, and small," and requires the integrated deployment of resources to ensure the security of trading and user information [Leng et al. 2018]. Moreover, since the COVID-19 pandemic, countries around the world have been facing food and environmental crises to varying degrees. The vulnerability of the agricultural supply chain has seriously affected people's everyday lives, and

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an efficient agricultural supply chain management mechanism is urgently needed.

The emergence of blockchain technology has the potential to solve the problem of agricultural supply chain management. With features such as transparency, traceability, immutability, irreversibility, point-to-point encryption, and smart contracts [Hughes et al. 2019], blockchain technology has been confirmed as a disruptive innovation and has attracted extensive attention from governments, mainstream financial institutions, capital markets, technology companies, and research institutions [Kassen 2022]. Many scholars have confirmed that blockchain is conducive to the coordinated operation of agricultural supply chain networks and to improving supply chain performance. Wang et al. (2022) argue that blockchain, with its characteristics of immutability, decentralization, and traceability, can provide a reliable and effective solution for agricultural supply chain management. Prashar et al. (2020) contend that the data on the blockchain is time-stamped, transparent, and secure, and if there is any problem, the data can be traced quickly and accurately; thus, the blockchain can be used to realize the automatic traceability and management of agricultural data. Li et al. (2020) conducted a convenience analysis of sustainable e-agriculture based on blockchain technology and found that the convenience under blockchain technology increased by more than 15% compared with traditional e-agriculture. Furthermore, relevant practices have highlighted the huge application prospects of blockchain in the agricultural supply chain. For example, Walmart deployed a blockchain system to track leafy greens [Kamath 2018], and JD.com applied blockchain technology to its beef supply chain. The American company Ripo Limited introduced blockchain into the management of the tomato supply chain and used sensors to upload tomato growth environment parameters to ensure the quality of tomatoes in real time.

Despite the evidence that blockchain technology has the potential to improve supply chain performance, the research and application of blockchain technology in agricultural supply chain management is still in the nascent stage. According to the 2019 Gartner report, most of the supply-chain projects based on blockchain technology have remained at either the pilot or proof-of-concept stage. The majority of Fortune 100 companies use blockchain technology, but the investment rate in blockchain technology has dropped since 2019. Bhatt et al. argue that blockchain is still an emerging technology and its application prospects need to be analyzed by researchers and inventors [Bhatt et al. 2020].

The prospect of promoting high-quality development of agriculture and rural areas by using blockchain technology is highly valued by countries around the world, but the related application research of blockchain in the agricultural field has been relatively limited [Kshetri 2020]. When there is uncertainty or a lack of understanding about the challenges that the widespread adoption of new technology will bring to the industry, the adoption of the technology will naturally be slow. Therefore, it is necessary to explore the reasons why blockchain technology is not widely used in the agricultural supply chain. To this end, researchers need to systematically review the existing literature and identify the challenges which hinder the adoption of blockchain technology in the agricultural supply chain to better use blockchain to solve problems such as food safety, non-point source pollution and financial exclusion in the agricultural supply chain management, and to promote the formation of decentralized social governance structures based on blockchain such as targeted poverty alleviation, rural link rectification, rural asset management, and rural e-commerce integration and innovation.

This study aims to quantitatively and comprehensively review the existing fragmented literature on blockchain technology, and to use social network analysis (SNA) to identify the key obstacles to the widespread adoption of blockchain technology in agricultural supply chain management, and also to provide references and suggestions for accelerating the application of blockchain technology in agricultural supply chain management. To this end, the study proposes the following four research objectives: 1) to analyze the research hotspots and development trends of blockchain technology applied in agricultural supply chain management; 2) to summarize the factors affecting the widespread adoption of blockchain technology in the agricultural supply chain; 3) to rank these summarized influencing factors and find out the relationship between them; 4) to determine the key factors and put forward specific reference suggestions.

The rest of this paper is organized as follows. Section 2 presents a systematic analysis of the application status of blockchain technology in agricultural supply chain management by using the systematic literature review (SLR) method. Section 3 describes the research methods and steps for data collection and analysis. Section 4 presents the results and discussions, followed by the conclusions and policy recommendations in Section 5. The research prospects are proposed in Section 6.

SYSTEMATIC LITERATURE REVIEW (SLR)

SLR is a literature review method that systematically collects, collates, analyzes, and evaluates existing research results to answer specific research questions [Staples et al. 2007], which can reduce researchers' subjective bias and improve rigor and repeatability. With the development of computer technology, data visualization techniques have gradually matured, and the analysis results of SLR can be displayed through knowledge graphs.

In recent years, research into and the application of blockchain technology have seen explosive growth [Buterin 2014], and there is increasing research on blockchain technology and its application in the agricultural supply chain [Al-Jaroodi and Mohamed 2019]. However, the existing review studies were carried out during an earlier time period when there were not enough studies conducted and the analysis was also limited, which failed to explore the important research topics and research potential in the field. To overcome this limitation, the present study first adopts the SLR method to conduct a comprehensive analysis of the accumulated knowledge in this field and draws the relevant visualization map using the VOSviewer software to obtain an objective and comprehensive research hotspot and development trend.

Data sources

The data were gathered from the Web of Science (WOS) Core Collection, the retrieval type was "TS=blockchain" & "TS=agri*", the literature type was restricted to paper (not including review papers), and the language was English. A total of 480 articles published as of March 11, 2023 had been retrieved.

Author-keyword network analysis

The number of articles published by an author is one of the important indicators to measure the academic level of an author. Paying attention to the literature published by the core authors in a certain field can help us understand the field more quickly and easily [Carpenter et al. 2014]. The author collaboration network demonstrates the extent of researchers' contributions to the blockchain adoption barriers field and their collaborative relationships with each other. Keywords, known as the real index of the subject area of an article, can best represent the subject content of an article [Kevork et al. 2009]. Thus, paying attention to high-frequency keywords can indicate the research focus of the blockchain technology applied in agricultural supply chain management. In this study, author and keyword were taken as nodes to obtain the visualization diagram of the author-keyword two-mode network in Figure 1.

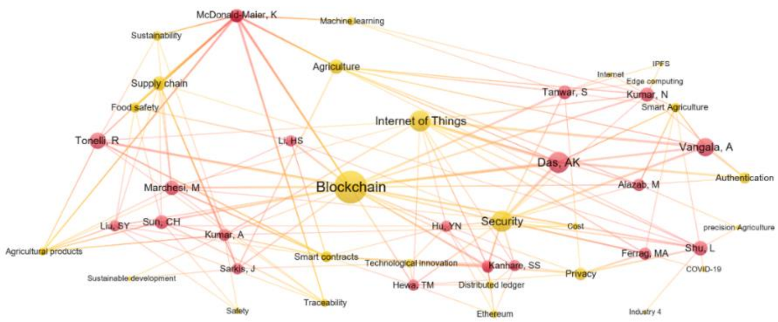

Fig. 1. Author-keyword two-mode visual map

In Figure 1, nodes in light red represent authors and nodes in yellow represent keywords. The size of the author and keyword nodes represents the number of papers published by an author and the frequency of occurrence of a keyword, respectively, and the line between the nodes represents the cooperative relationship. Das, AK; Vangala, A; and Tonelli, R are the top three core authors, and their research serves as a link between the past and the future of blockchain technology. Das mainly studied the development process of blockchain technology in intelligent agriculture. Vangala focused on security architecture, opportunities, and challenges based on the Internet of Things (IoT) and consensus mechanisms in smart agriculture. Tonelli studied the sustainability of information technology application in the food supply chain. These studies are the basis of recent research in this field and should be given high attention. By observing the node size of keywords, we can analyze that blockchain, IoT, distributed ledger, smart contract, Ethereum, cloud computing, and other information technologies are the current research hotspots in the development of agricultural informatization. Traceability is the most widely used function of blockchain technology in agricultural supply chain management. Furthermore, concerns have been raised about security, privacy, and the cost of adopting blockchain technology.

Time-keyword network analysis

To further analyze the development trend of blockchain technology in agricultural supply chain management, this study takes time and keywords as nodes to obtain the time-keyword two-mode visualization map in Figure 2.

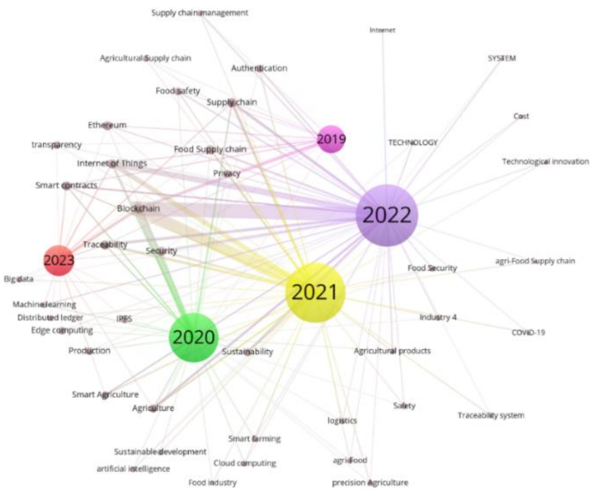

Fig. 2. Time-keyword two-mode visualization map

As can be seen from Figure 2, the nodes representing time increased in size with every passing year, indicating that this field has received increasing research attention from 2019 to 2022. To clearly see the evolution of research hotspots in this field, we used VOSviewer software to generate keyword tag views based on time and keyword dimensions in Figure 3. The color of nodes in the view represents the year of keyword occurrence, and the size of nodes represents the frequency of keyword co-occurrence.

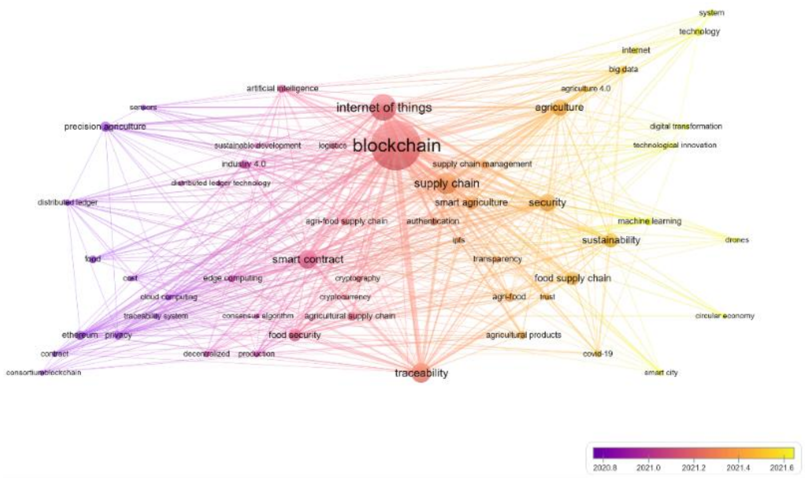

Fig. 3. Keyword tag views by year

As can be seen from Figure 3, research on the application of blockchain technology in the agricultural field only began to appear in 2020, indicating that this topic is relatively new and still worthy of in-depth discussion. With the development of the Industry4.0 era, agricultural development has also entered the Agriculture4.0 era. The traceability feature of blockchain technology has been largely used in agricultural supply chain management, whereas the consensus mechanism and smart contract features have been applied in intelligent agriculture. Since 2021, there has been increased concern about the transparency, security, sustainability, and reliability features of blockchain technology, indicating that there are still some challenges in the application of this technology in agricultural development. However, there is no doubt that digital reform and technological innovation are irreversible trends in today's world. It is important to promote the adoption and application of information technology for the development of industry, especially the relatively backward informatization development of agriculture.

RESEARCH METHODS

Content analysis

Based on the results of SLR, in-depth literature screening was conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The PRISMA checklist is mainly used to improve and enhance the quality of systematic review and meta-analysis reports. The researchers first screened and analyzed the previous studies to identify the obstacles and challenges affecting the promotion and application of blockchain technology in the agricultural supply chain. The literature selection process includes four stages: identification, preliminary screening, eligibility assessment, and comprehensive inclusion [Jüni and Egger 2009]. Considering that data is constantly updated, this study used December 2022 as the retrieval time, and related research results were collected and sorted based on the PRISMA guidelines. The literature screening process is shown in Figure 4.

For the literature search, we used "TS= Blockchain Barriers" and "TS= Agri-" or their synonyms to retrieve relevant articles from the Web of Science. The literature type was restricted to paper and the language was English. A total of 124 papers were obtained, and 5 highly cited papers of core authors identified in the SLR stage were added. After reading the titles and abstracts, we eliminated 28 articles unrelated to the adoption of blockchain technology, 29 articles only related to the necessity and benefits of blockchain application but unrelated to obstacles, and 7 articles whose full text could not be obtained. Finally, 65 articles related to blockchain technology were selected for in-depth reading.

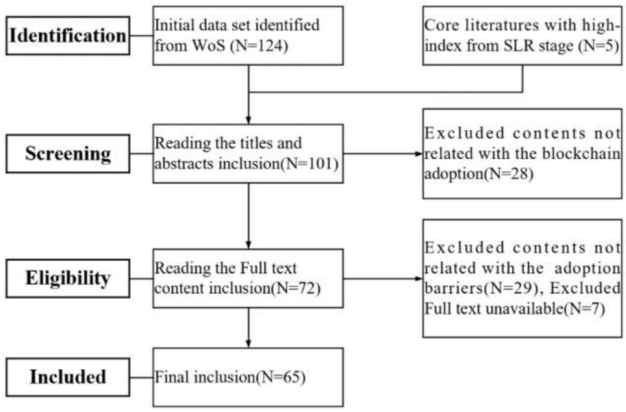

Fig. 4. Literature screening process based on PRISMA guidelines

Policy orientation is crucial for the proliferation of new technologies, and blockchain technology has attracted high attention from governments all over the world. In addition to the selected 65 papers, this study also considered key policy documents, such as the "National Strategy for Critical and Emerging Technology" released by the White House in October 2020, the "Distributed Ledger Technology: Beyond Blockchain" released by the British government in 2018, and the "German National Blockchain Strategy", jointly published by the German Ministry of Economy, Energy and Finance in 2019. We also included a few industry research reports, such as the Global Blockchain Survey report released by Deloitte in 2020. Based on an in-depth reading of these papers and documents and through discussion with scholars in the industry, obstacles and challenges to the adoption of blockchain technology in agricultural supply chain management were extracted and summarized. For example, the effects of different rules in different regions or industries indicated institutional standard consistency, the effect of system delay indicated system efficiency, centralized control represented accessibility, modular operation and the willingness of operators to embrace new technologies indicated perceived ease of use, and the influence of cultural or technological differences indicated the compatibility of blockchain technology. Furthermore, several scholars have confirmed that the degree of infrastructure perfection affects users' willingness to adopt technology; thus, this factor was also considered in this study. Many previous studies have found that initial investment cost also affects users' willingness to adopt technology. However, in the analysis of relevant literature, this study found that the application and promotion of blockchain technology included the cost of initial investment and later system maintenance; therefore, this study considered sustainability and perceived cost as separate influencing factors.

Co-occurrence matrix and frequency analysis

The co-occurrence matrix presents a summary of the information association in the original data space. The value on the diagonal represents the frequency of occurrence of an item in the sample literature, while the other values represent the frequency of co-occurrence of two items in the same literature. The higher the frequency of co-occurrence, the closer the relationship between the two items, and it also represents the focus of the field [Dai et al. 2020]. The summarized influencing factors were sorted, and 38 key influencing factors were identified. To facilitate subsequent statistical analysis, the identified influencing factors were numbered A1 to A38, and the frequency statistics of influencing factors are shown in Table 1.

Table 1. Frequency statistics of influencing factors

No.	Influencing factors	Freq.	No.	Influencing factors	Freq.
A1	Perceived Cost	17	A20	Accessibility	3
A2	Policy Support	16	A21	Data Validity	2
A3	Establishment of Consensus Network	15	A22	Market Competitive Environment	1
A4	Privacy and Security	13	A23	Technological Maturity	1
A5	Stakeholder Attitude	10	A24	Technological Innovation	1
A6	Verifiability of Results	9	A25	Flexibility	1
A7	Scalability	9	A26	Market Competition Environment	1
A8	Infrastructure	8	A27	Technological Comparative Advantage	1
A9	Interoperability	7	A28	Degree of Applicability and Match	1
A10	Lack of Knowledge and Understanding	7	A29	Lower Demand for Labor	1
A11	Consistency of System Standards	6	A30	Over-publicity	1
A12	System Operation Efficiency	6	A31	Conformity of Institutional Standards	1
A13	Sustainability	6	A32	Scale	1
A14	Regulatory Uncertainty	6	A33	Decision-Maker Level	1
A15	Transparency	6	A34	Application and Matching Degree	1
A16	Energy Consumption	5	A35	Industry Boycott	1
A17	Insufficient Cognition and Understanding	3	A36	Extensible	1
A18	Complexity	3	A37	Compatibility	1
A19	Perceived Ease of Use	3	A38	Perceived Risk	1

Social network analysis (SNA)

SNA is a quantitative analysis method based on graph theory and a variety of mathematical methods. It is developed from network theory and organically combined with social theory, statistics, and computational methodology to investigate social relations and social structure [Granovetter 1988]. To analyze the importance of and the relationship between the influencing factors based on SNA, UCINET and NetDraw software were used to visualize the co-occurrence matrix of factors influencing the application of blockchain technology in agricultural supply chain management (only factors with frequency >2 were considered). The visualization diagram is presented in Figure 5, and the analysis results of network evaluation indexes are shown in Table 2.

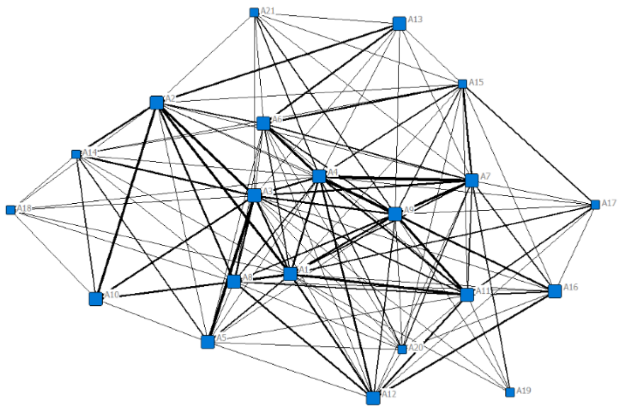

Fig. 5. Visualization diagram of influencing factors

Table 2. Network evaluation index analysis results

Lab.	Clus.	Between-ness cen.	Closeness cen.	Eigenvec-tor cen.	Cluster-ing	Degree	Degree cen.	Harmoni-c cen.	Pager-ank	Constra-int	Effective -size
A1	C0	0.07	0.91	0.29	0.63	18	0.9	19	0.08	0.20	7.33
A2	C0	0.03	0.77	0.23	0.69	14	0.7	17	0.06	0.22	5.00
A3	C0	0.07	0.91	0.28	0.59	18	0.9	19	0.08	0.19	7.89
A4	C1	0.05	0.91	0.29	0.65	18	0.9	19	0.08	0.20	7.00
A5	C0	0.01	0.71	0.21	0.80	12	0.6	16	0.04	0.22	3.17
A6	C1	0.02	0.80	0.26	0.74	15	0.75	17.5	0.05	0.21	4.60
A7	C1	0.04	0.83	0.26	0.68	16	0.8	18	0.07	0.21	5.75
A8	C0	0.03	0.80	0.25	0.72	15	0.75	17.5	0.06	0.21	4.87
A9	C1	0.04	0.87	0.28	0.67	17	0.85	18.5	0.07	0.21	6.29
A10	C0	0.00	0.61	0.12	0.95	7	0.35	13.5	0.04	0.31	1.29
A12	C1	0.01	0.71	0.22	0.88	12	0.6	16	0.05	0.24	2.33
A11	C1	0.02	0.77	0.24	0.77	14	0.7	17	0.06	0.22	4.00
A15	C1	0.02	0.74	0.22	0.68	13	0.65	16.5	0.04	0.21	4.85
A13	C1	0.00	0.63	0.15	0.96	8	0.4	14	0.03	0.28	1.25
A14	C0	0.01	0.67	0.17	0.80	10	0.5	15	0.04	0.25	2.80
A16	C1	0.00	0.69	0.20	0.89	11	0.55	15.5	0.04	0.24	2.09
A19	C1	0.00	0.57	0.10	1.00	5	0.25	12.5	0.02	0.31	1.00
A17	C1	0.00	0.63	0.15	0.96	8	0.4	14	0.03	0.27	1.25
A18	C0	0.00	0.61	0.12	0.95	7	0.35	13.5	0.02	0.30	1.29
A20	C1	0.00	0.71	0.22	0.89	12	0.6	16	0.03	0.23	2.17
A21	C1	0.00	0.63	0.15	0.96	8	0.4	14	0.02	0.28	1.25

After comparing the key influencing factors by the node size, we further explored the relationship between the influencing factors. The CONCOR method was used to conduct a cohesive subgroup analysis of the influencing factors, and the core-edge analysis function was used to conduct core-edge analysis. The cohesive subgroup analysis map and the density matrix are shown in Figure 6 and the core-edge analysis map is shown in Figure 7.

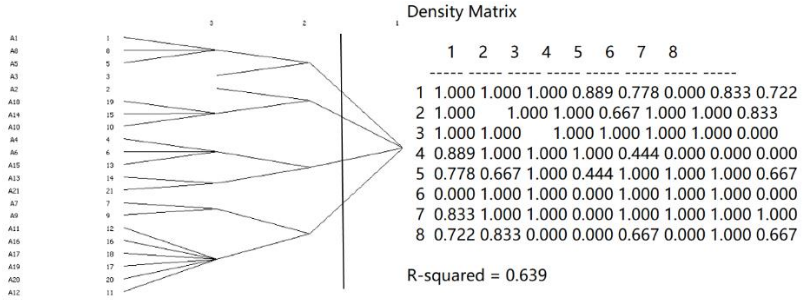

Fig. 6. Subgroup analysis map and density matrix

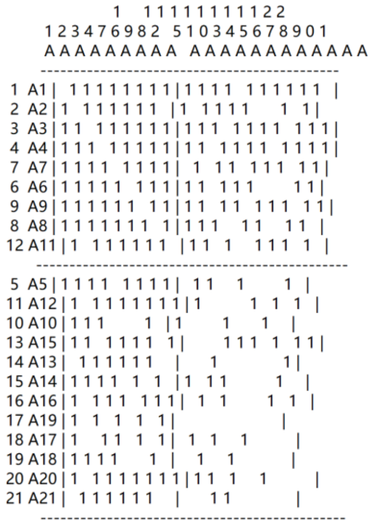

Fig. 7. Core-edge analysis map

RESULTS AND DISCUSSIONS

This study used SNA to determine the rank and influence degree of the factors affecting the promotion and application of blockchain technology in agricultural supply chain management. SNA is a quantitative tool to study network relations and the network evaluation indexes include overall network density, centrality, structural hole, core-edge structure, and cohesiveness analysis [Butts 2008]. The analysis results are discussed below.

Frequency analysis of influencing factors

Statistically speaking, the greater number of times an item occurs in a list, the more important it is. In this study, 38 influencing factors related to the application of blockchain technology in the agricultural supply chain were extracted in Table 1. The top three influencing factors with the highest frequencies were Perceived Cost (A1, 17 times), Policy Support (A2, 16 times), and Establishment of Consensus Network (A3, 15 times).

Overall network density analysis

The overall network density indicates the closeness of the relationship between all nodes in the network. Generally, the higher the network density, the closer the connection between all action subjects in the network [Singh et al. 2022]. By importing the co-occurrence matrix into the UCINET software, the overall network density was found to be 0.614 (>0.500) and the number of edges was 129. The overall network density value is relatively large, indicating that the extracted influencing factors are closely related to each other.

Centrality analysis

Centrality analysis is mainly performed to measure the influence of a node in the network. The larger the measurement value, the more important the node in the network. Centrality can be expressed by degree centrality, betweenness centrality, and closeness centrality [Singh et al. 2022].

Degree centrality is an index used to measure the position of a node in the network; the node with a higher degree occupies the central position in the network. Thus, the higher the degree of an influencing factor, the more connection it has with other influencing factors. In this study, Perceived Cost (A1), Establishment of Consensus Network (A3), and Privacy and Security (A4) had the highest degree, followed by Interoperability (A9) and Scalability (A7), indicating that concerns about the cost and technological maturity of blockchain are important constraints on its adoption in the agricultural supply chain.

Betweenness centrality reflects the nodes which act as a "bridge" in the network, controlling the information flow in the network. The results of between centrality are similar to degree centrality, with Perceived Cost (A1), Establishment of Consensus Network (A3), and Privacy and Security (A4) being the top three nodes, followed by Scalability (A7) and Interoperability (A9).

Closeness centrality measures how close a node is to other nodes in the network. The lower the proximity, the stronger the independence of the node. In this study, Perceived Cost (A1), Establishment of Consensus Network (A3), and Privacy and Security (A4) are the top three nodes with the highest degree of proximity to the center, which is consistent with the analysis results of degree centrality and betweenness centrality. The top three nodes with the lowest degree of proximity to the center are Perceived Ease of Use (A19), Complexity (A18), and Lack of Knowledge and Understanding (A10), indicating that the operator's knowledge and mastery of technology influence their decision about whether to adopt the technology.

Structural hole analysis

Structural hole refers to the phenomenon of no direct connection or discontinuous connection between nodes in the network, indicating a node's ability to control resources in the network. There are two main measurement indicators: constraint and effective size [Brass and Behavior 2022]. The smaller the constraint value, the larger the number of resources controlled by a node; the measurement criterion of effective size is opposite to that of constraints. As shown in Table 2, the top three nodes with the lowest constraint values and the highest effective sizes are Establishment of Consensus Network (A3), Perceived Cost (A1), and Privacy and Security (A4), indicating that these three influencing factors have strong control over other factors and are less restricted by other factors.

Cohesive subgroup analysis

Cohesive subgroup analysis reveals the actual or potential relationships among nodes in the network. If there is a cohesive subgroup in a certain network, and the density of the cohesive subgroup is high, it means that the nodes within the cohesive subgroup are closely connected and frequently interact with each other for information sharing and cooperation [Gao et al. 2022]. As shown in Figure 6, the network constructed in this study has eight subgroups. Subgroup 8 includes six influencing factors (A11, A16, A17, A19, A20, and A12), followed by Subgroups 1, 4, and 5, which include three influencing factors each. Both Subgroup 2 and Subgroup 3 include only one factor each, indicating that A3 and A2 are not connected with any other factors and are relatively independent.

Core-edge analysis

Core-edge analysis distinguishes the core region and the edge region according to the closeness of the connection between nodes in the network, so as to achieve the purpose of quantitative analysis of the network location structure [Gao et al. 2022]. As shown in Figure 7, there are 9 nodes in the core region and 12 nodes in the edge region, which is consistent with the display results of the visualization map in Figure 5, indicating that the application maturity of blockchain technology and the perception of stakeholders are crucial in the adoption of blockchain technology in the agricultural supply chain.

CONCLUSION AND POLICY RECOMMENDATIONS

Pooled analysis results

To sum up, the results of centrality analysis and structural hole analysis are consistent with the frequency statistics, indicating that Perceived Cost (A1), Establishment of Consensus Network (A3), and Privacy and Security (A4) are the key factors affecting the application of blockchain in the agricultural supply chain. Although the frequency of Policy Support (A2) is high (16 times), it does not have a connection with any other factor and belongs to a single-factor subgroup. In addition, it occupies the middle position in centrality analysis. This indicates that policy support by the government directly affects the willingness to adopt blockchain technology. Furthermore, A1, A2, A3, and A4 are placed in the core region of the core-edge map, which further verifies the critical influence of these four factors. Among the nine core factors, five factors (A3, A4, A6, A7, and A9) are related to the characteristics of the technology itself, indicating that whether or not the technology is efficient is the basic factor affecting its promotion, which is consistent with the results of previous research. The other four core factors are related to cost input (A1 and A8) and policy system (A2 and A11). Thus, improving infrastructure while reducing the input cost and increasing government incentives will have a strong influence on improving the willingness to adopt blockchain technology.

Policy recommendations

This study used SNA to identify the factors influencing the adoption of blockchain technology in agricultural supply chain management. Based on the study findings, the following suggestions and policy recommendations are put forward:

Technological factors are the main factors affecting the adoption of blockchain technology. It is necessary to further improve the stability, scale, and security of the blockchain technology.

Cost factors greatly influence the adoption enthusiasm of users, especially in the agricultural industry with small-scale and dispersed individual businesses. It is suggested that the local government can bear the cost of infrastructure construction and train professionals in blockchain technology.

Policy incentives can further improve users' willingness to adopt blockchain technology in agricultural supply chain management. The government can introduce and implement relevant tax incentives to promote blockchain technology.

RESEARCH PROSPECTS

In this study, the SNA method was used to systematically analyze the factors influencing the adoption of blockchain technology in agricultural supply chain management. The study findings will help practitioners in this field more clearly understand the application challenges of blockchain technology, promote the development of agricultural informatization, and provide suggestions for local agricultural enterprises on how to effectively adopt blockchain technology, which will have positive practical significance for promoting the development of blockchain technology in agriculture.

This study also has certain limitations. First, the study was mainly based on statistical data from previous studies and the opinions of a few field experts, and did not conduct a large-scale questionnaire survey based on an empirical model. The influencing factors can be classified according to the technology-organization-environment (TOE) framework and an empirical model can be developed based on the technology acceptance model (TAM) to obtain more accurate verification results based on a large sample survey. In addition, taking into account the fact that users' adoption intentions change over time, dynamic empirical research should be conducted on the influencing factors of blockchain technology in agricultural supply chain management.

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ORIGINAL PAPER

ASSESSING THE LOGISTICS MARKET PERFORMANCE OF DEVELOPING COUNTRIES BY SWARA-CRITIC BASED CoCoSo METHODS

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ABSTRACT. Background: The logistics market performance of developing countries has been measured by the Agility Emerging Markets Logistics Index [AEMLI] report since 2014. The main objective of this study is to propose a new model to assess the logistics market performance of developing countries and rank them based on this performance. Correspondingly, the AEMLI indicators were selected as the main criteria for assessing the logistics market performance of developing countries in this study.

Methods: In the current study, the AEMLI indicators, which are domestic logistics opportunities [DLO], international logistics opportunities [ILO], business fundamentals [BF] and digital readiness [DR], were used as criteria to assess the logistics market performances of developing countries. First, the weights of the criteria were computed by a combination of subjective [SWARA] and objective [CRITIC] methods. Then, the CoCoSo method was used to rank developing countries according to their logistics market performance.

Results: The findings indicate that BF is the most significant criterion, followed by ILO, DR and DLO. Based on the results of the proposed model, China, India, the United Arab Emirates [UAE], Malaysia, and Saudi Arabia had the best logistics market performance in 2022, while Angola, Myanmar, Mozambique, Venezuela, and Libya had the worst logistics market performance in 2022. Additionally, some differences in the ranking of developing countries according to logistics market performance can be observed in the proposed model compared to the AEMLI 2023 report.

Conclusion: To the best of the author's knowledge, this is the first study to examine logistics market performance through the combination of two weighting methods (both subjective and objective). The current study also contributes to the existing literature by providing insight into logistics market performance for carriers, shippers, distributors, policy makers, and others who focus on the world's emerging markets.

Keywords: logistics, emerging markets, SWARA, CRITIC, CoCoSo

INTRODUCTION

Logistics plays a key role in the development of the global economy by enhancing international trade. During the COVID-19 pandemic, logistics experienced significant growth all around the world. The logistics industry worldwide was worth approximately 8.5 trillion Euros in 2021 and is expected to reach almost 14 trillion Euros by 2027. In parallel to this, global total logistics costs soared to 9 trillion U.S. dollars in 2020. That represents 10.7 percent of the global Gross Domestic Product [GDP] of 85.24 trillion U.S. dollars that year [Placek, 2023]. Particularly in the last few years, the cost of logistics, transport, and warehousing has increased exponentially due to the uncertainty and lack of resources in the logistics industry.

According to the latest report published by Gi Group [2022], the size of the global logistics market has been growing rapidly worldwide. In 2018, the global economic value of logistics was 8 trillion U.S. dollars, but by the end of 2024, it is estimated to exceed that by about 25% compared to 2018, reaching 9.9 trillion U.S. dollars. Moreover, developing countries are playing an active role in the growth of the global logistics market. Correspondingly, the importance of emerging markets in global

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logistics activity continues to increase. For instance, about 60% of the global logistics market is dominated by developing countries. 45% of the global logistics market is occupied by the Asia-Pacific region, followed by Africa, South America, and the Commonwealth of Independent States [CIS] region, which accounts for about 15% of the market. There are also interesting developments in other regions, such as the Middle East and North Africa [Gi Group, 2022, p. 4-6]. For this reason, it is important to compare the logistics performance of different nations.

Some international organizations, such as the World Bank [WB], Transport Intelligence [T*i*] and Agility, have developed indices to measure the logistics performance of nations. For instance, the Logistics Performance Index [LPI] and the Agility Emerging Markets Logistics Index [AEMLI] have been developed by the WB and Ti/Agility, respectively. The AEMLI report focuses on the assessment of the logistics market performance of 50 of the world's most promising emerging markets. This index has examined four key areas, namely domestic logistics opportunities [DLO], international logistics opportunities [ILO], business fundamentals [BF] and digital readiness [DR]. To determine the logistics market performance of 50 leading global emerging markets, data was collected from prestigious institutions around the world, including the International Monetary Fund [IMF], the World Economic Forum [WEF], the WB and T*i*. As a result, the index provides a snapshot of each country's current performance and future potential as a globally significant logistics market and investment destination [Agility, 2023, p.11].

In recent years, there has been an increasing amount of literature on the logistics performance of nations using Multi-Criteria Decision-Making [MCDM] methods. For example, the logistics performance index [LPI] of OECD countries [Çakır, 2017; Yıldırım and Adıgüzel Mercangöz, 2020; Çalık et al., 2023], Balkan and Western Balkan countries [Mešić et al., 2022; Stević et al., 2022], Central and Eastern European countries [Isik et al., 2020], European Union [EU] countries [Ulutaş and Karaköy, 2019], and Turkey and the EU [Senir, 2021] have all been examined by hybrid MCDM methods. However, there has been relatively little literature published on logistics market performance using MCDM methods. Kara et al. [2022] investigated the logistics market performance of developing countries using Entropy and MABAC methods. Another study, conducted by Kara and Yalçın [2022], reviewed the digital logistics market performance of developing countries using MEREC and RAFSI methods. Previous studies indicate that much of the current literature is concentrated on the LPI. A limited number of studies have reviewed the logistics market performance of countries. Additionally, much of the research in the existing literature has been conducted using a single approach, either subjective or objective.

Accordingly, the main objective of this study is to propose a new model to assess the logistics market performance of developing countries and to rank them based on their logistics market performance. At first, the weights of criteria were computed by a combination of subjective [SWARA] and objective [CRITIC] methods. Then, developing countries were ranked according to their logistics market performance by the CoCoSo method. The rest of this paper is structured as follows: the second section describes the MCDM methods used in the study; the third section is concerned with applications and results, and presents the findings of the study; finally, the conclusion gives a summary and critique of the findings.

LITERATURE REVIEW

The last decade has seen the publication of a significant number of studies examining the logistics performance of countries using MCDM methods. Table 1 provides a brief synopsis of the relevant literature.

Table 1. Overview of Previous Studies

Author(s)	Year	Indicators	Methods	Topic
Gergin & Baki	2015	WB LPI	AHP & TOPSIS	Analysis of the LPI of regions in Turkey
Çakır	2017	WB LPI	CRITIC & SAW & Peter's Fuzzy Regression	Measurement of the LPI of OECD countries
Candan	2019	WB LPI	Fuzzy AHP & Grey Relational	Evaluation of the LPI of selected countries in the OECD
Orhan	2019	WB LPI	ENTROPY & EDAS	Comparison of the LPI of Turkey and EU countries
Ulutaş & Karaköy	2019	WB LPI	SWARA & CRITIC & PIV	Analysis of the LPI of EU countries
Yıldırım & Adıgüzel Mercan	2020	WB LPI	Fuzzy AHP & ARAS-G	Evaluation of the LPI of OECD countries
Isık et al.	2020	WB LPI	SV & MABAC	Assessment of the LPI of Central and Eastern European countries
Adıgüzel et al.	2020	WB LPI	COPRAS-G	Examination of the LPI for a selected period: EU and 5 EU candidate countries
Senir	2021	WB LPI	CRITIC & COPRAS	Comparison of domestic logistics performance of Turkey and EU countries
Mešić et al.	2022	WB LPI	CRITIC & MARCOS	Evaluation of the LPI of the Western Balkan countries
Arıkan Kargı	2022	WB LPI	ENTROPY & WASPAS	Evaluation of the LPI of OECD countries
Kara et al.	2022	AEMLI Report	ENTROPY & MABAC	Determination of the logistics market performance of developing countries
Kara & Yalçın	2022	AEMLI & DCI Report	MEREC & RAFSI	Analysis of the digital logistics market performance of 19 developing countries
Çalık et al.	2023	WB LPI	AHP & TOPSIS, VIKOR & CODAS	Evaluation of the logistics performance of 160 OECD countries

This overview of previous studies indicates that the LPI has been widely used to evaluate the logistics performance of countries. In particular, the assessment and comparison of logistics performance were conducted using integrated MCDM methods. Most studies that evaluate logistics performance have been carried out with LPI by using various MCDM methods. However, a limited number of studies have examined the logistics market performance of countries. So far, no studies have been found that investigate logistics market performance by combining two weighting methods. Correspondingly, this study aims to contribute to this area of research by proposing a new model.

METHODOLOGY

In this study, hybrid MCDM methods were applied to evaluate the logistics market performance of developing countries. In this regard, two weighting methods, namely SWARA and CRITIC, were used to calculate the weights of criteria. The ranking of alternatives was carried out by the CoCoSo method. The steps of the methods used in this study are presented below.

Stepwise Weight Assessment Ratio Analysis [SWARA] Method

The Stepwise Weight Assessment Ratio Analysis [SWARA] method was introduced by Kersuliene, Zavadskas and Turkis in 2010. In this method, which is based on weightings, the relative importance and the initial prioritization of alternatives for each attribute are chosen by the decision-maker, and then the relative weight of each attribute is determined. The steps of the SWARA method are as follows [Keršuliene et al., 2010; Alinezhad & Khalili, 2019]:

Step 1. The Initial Prioritization of Attributes

First, the attributes are prioritized in terms of relative importance, determined by decision-makers.

Step 2. The Coefficient (*K*)

The coefficient (*K*) of an attribute for each decision-maker is calculated using Eq. [1].

$$K_j = \begin{cases} 1 & if \quad j = 1 \\ S_j + 1 & if \quad j > 1 \end{cases}; \qquad [1]$$

$$j = 1, \dots \dots \dots \dots \dots \dots, n$$

Step 3. The Initial Weight

At this stage, Eq. [2] is used to compute the initial weight of an attribute for each decision-maker.

$$K_j = \begin{cases} 1 & if \quad j = 1 \\ \dfrac{q_j}{K_j} & if \quad j > 1 \end{cases}; \qquad [2]$$

$$j = 1, \dots \dots \dots \dots \dots \dots, n$$

Step 4. The Relative Weight

Eq. [3] is applied to determine the relative weight of an attribute for each decision maker.

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_i} \qquad [3]$$

Step 5. The Final Ranking of Attributes

By determining the relative weight of each attribute, the values are arranged in descending order, producing the final ranking.

Criteria Importance Through Intercriteria Correlation [CRITIC] Method

The Criteria Importance Through Intercriteria Correlation [CRITIC] method was introduced by Diakoulaki, Mavrotas and Papayannakin in 1995. It is mostly utilized to calculate the weight of attributes and it is an objective weighting method. The attributes in the present method do not conflict with one another, and the decision matrix is used to calculate the weights of the attributes. The steps of the CRITIC method are as follows [Diakoulaki et al., 1995; Alinezhad & Khalili, 2019]:

Step 1. The Normalized Decision Matrix

In order to normalize the positive and negative attributes of the decision matrix, Eqs. [4] and [5] are utilized, respectively.

$$x_{ij} = \frac{r_{ij} - r_i^-}{r_i^t - r_i^-}; \qquad [4]$$
$$i = 1, \dots \dots, m \quad j = 1, \dots \dots, n$$

$$x_{ij} = \frac{r_{ij} - r_i^+}{r_i^- - r_i^+}; \qquad [5]$$
$$i = 1, \dots \dots, m \quad j = 1, \dots \dots, n$$

where x_{ij} represents a normalized value of the decision matrix for the *i*th alternative for the *j*th attribute, $r_i^+ = \max(r_1, r_2, \dots, r_m)$ and $r_i^- = \min(r_1, r_2, \dots, r_m)$.

Step 2. The Correlation Coefficient

Eq. [6] is used to determine the correlation coefficient among attributes.

$$\rho_{jk} = \sum_{i=1}^{m}(x_{ij} - \bar{x}_j)(x_{ik} - \bar{x}_k) \Big/ \sqrt{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2 \sum_{i=1}^{m}(x_{ik} - \bar{x}_k)^2} \qquad [6]$$

where $\bar{x}_j$ and $\bar{x}_k$ display the mean of the *j*th and *k*th attributes. $\bar{x}_j$ is computed from Eq. [7]. $\bar{x}_k$ is obtained in the same way. ρ_{jk} is the correlation coefficient between the *j*th and *k*th attributes.

$$\bar{x}_j = \frac{1}{n}\sum_{j=1}^{n} x_{ij}; \qquad [7]$$

$$i = 1, \dots \dots \dots \dots \dots \dots, m$$

Step 3. The Index (C)

At first, the standard deviation of each attribute is estimated by Eq. [8].

$$\sigma_j = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{ij} - \bar{x}_j)^2}; \qquad i \qquad [8]$$

$$= 1, \dots \dots \dots \dots, m$$

Then, the index (C) is calculated using Eq. [9].

$$C_J = \sigma_j \sum_{k=1}^{n} (1 - \rho_{jk}); \quad j = 1, \dots \dots \dots \dots \dots, n \qquad [9]$$

Step 4. Weights of Attributes

The weights of the attributes are determined by Eq. [10].

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j}; \quad j = 1, \dots \dots \dots \dots \dots, n \qquad [10]$$

For the final ranking, the attribute weights are ranked in descending order.

Calculation of the Aggregated Weighting Method

By using Eq. [11], the aggregated weight is computed [Ighravwe & Babatunde, 2018; Ali et al., 2020];

$$W_{Aggregated} = \Delta W_{sj} + (1-\Delta)\, Woj \qquad [11]$$

where W_{sj} and W_{oj} represent the subjective and objective weights of the criteria respectively and Δ symbolizes the contribution factor. Keshavarz Ghorabaee et al. [2017] suggested using values of Δ from 0 to 1. For this study, Δ = 0.5 was selected.

Combined Compromise Solution [CoCoSo] Method

The Combined Compromise Solution [CoCoSo] was proposed by Yazdani, Zarate, Zavadskas and Turskis in 2019. This approach is based on an integrated simple additive weighting and exponentially weighted product model. It can function as a compendium of compromise solutions. To solve a CoCoSo decision problem, after determining the alternatives and the related criteria, the following steps are used [Yazdani et al., 2019]:

Step 1. The Initial Decision Matrix is Formed.

Step 2. The Normalized Decision Matrix

The normalization of criteria values is accomplished based on the compromise normalization equation.

$$r_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}; \qquad [12]$$

$$r_{ij} = \frac{x_{ij} - \max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}; \qquad [13]$$

Step 3. The Calculation of S_i and P_i Values

The total of the weighted comparability sequence and the whole of the power weight of comparability sequences for each alternative sum of the weighted comparability sequence and also an amount of the power weight of comparability sequences for each alternative are denoted as S_i and P_i, respectively.

$$S_i = \sum_{j=1}^{n} (w_j r_{ij}), \qquad [14]$$

this S_i value is determined based on a grey relational generation approach:

$$P_i = \sum_{j=1}^{n} (r_{ij})^{w_j} \qquad [15]$$

this P_i value is determined according to the WASPAS multiplicative attitude.

Step 4.

The relative weights of the alternatives are computed using the following aggregation strategies. In this step, three appraisal score strategies are used to generate the relative weights of other options, which are derived using Eqs. [16]-[18]:

$$k_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{m} (P_i + S_i)} \qquad [16]$$

$$k_{ib} = \frac{S_i}{\min_i S_i} + \frac{P_i}{\min_i P_i} \qquad [17]$$

$$k_{ic} = \frac{\lambda(S_i) + (1-\lambda)(P_i)}{\left(\lambda \max_i S_i + (1-\lambda) \max_i P_i\right)} \quad [18]$$

$$0 \leq \lambda \leq 1.$$

It is found that Eq. [16] expresses the arithmetic mean of the sums of the WSM and WPM scores, while Eq. [17] expresses a sum of relative scores of WSM and WPM compared to the best. Eq. [18] gives the balanced compromise of the WSM and WPM model scores. In Eq. [18] λ (usually λ = 0.5) is chosen by decision-makers. However, the flexibility and stability of the proposed CoCoSo can be affected by other values.

Step 5. The Final Ranking

The final ranking of the alternatives is determined based on k_i values (the more significant the better):

$$k_i = (k_{ia}k_{ib}k_{ic})^{\frac{1}{3}} + \frac{1}{3}(k_{ia}k_{ib}k_{ic}) \quad [19]$$

APPLICATION AND RESULTS

Results Obtained from the Subjective Method [SWARA]

Table 2 represents the initial prioritization of attributes based on the experts' opinions.

Table 2. The Initial Prioritization Matrix

Criteria	Decision Makers (DM)								Average Importance Scores
	DM_1	DM_2	DM_3	DM_4	DM_1	DM_2	DM_3	DM_4	
DLO	4	4	3	4	0.25	0.25	0.50	0.25	0.31
ILO	1	3	2	1	1.00	0.50	0.75	1.00	0.81
BF	2	1	1	2	0.75	1.00	1.00	0.75	0.88
DR	3	2	4	3	0.50	0.75	0.25	0.50	0.50

Using Eqs. [1], [2] and [3], the coefficient, the initial weight and the relative weight of the attributes for each decision-maker were computed. They are shown in Table 3.

Table 3. Results of s_j, K_j, q_j and w_j

Criteria	Average Importance Scores	The Comparative Value of the Average Importance Scores (s_j)	Coefficient Values (K_J)	Recalculated Weight (q_j)	Final Weight (w_j)
BF	0.88	-	1.0000	1.0000	0.3080
ILO	0.81	0.0700	1.0700	0.9345	0.2878
DR	0.50	0.3100	1.3100	0.7133	0.2197
DLO	0.31	0.1900	1.1900	0.5994	0.1846

Results Obtained from the Objective Method [CRITIC]

The decision matrix for assessing the logistics market performance of developing countries is presented in Table 4.

The normalized values of the decision matrix were calculated with respect to the positive or negative attributes as illustrated in Table 5.

The correlation coefficient was computed according to Eqs. [6] and [7] and is illustrated in Table 6.

The standard deviation of each attribute and the index (*C*) was calculated using Eqs. [8] and [9] and is shown in Table 7.

Table 4. Decision Matrix

Rank	Country	DLO	ILO	BF	DR	Rank	Country	DLO	ILO	BF	DR
1	China	8.47	9.75	7.11	6.63	26	Pakistan	5.16	4.63	4.13	5.06
2	India	8.04	7.45	5.94	7.61	27	Peru	4.72	5.12	4.48	4.58
3	UAE	5.60	5.89	9.10	7.37	28	Colombia	4.67	5.08	4.55	4.53
4	Malaysia	5.29	5.88	7.85	6.72	29	Ghana	4.61	4.44	5.00	5.14
5	Indonesia	6.34	5.89	5.77	6.21	30	Sri Lanka	4.49	4.73	4.32	5.12
6	Saudi Arabia	5.38	5.74	7.89	6.30	31	Argentina	4.87	4.63	4.24	4.68
7	Qatar	5.91	4.96	7.92	6.38	32	Tunisia	4.61	4.48	5.06	4.39
8	Thailand	5.11	5.98	5.77	6.04	33	Lebanon	4.81	4.61	3.79	4.80
9	Mexico	5.37	6.32	4.93	5.11	34	Nigeria	5.15	4.39	3.62	4.61
10	Vietnam	5.02	6.03	5.61	5.43	35	Bangladesh	5.02	4.48	3.53	4.63
11	Turkey	5.14	5.70	5.80	5.50	36	Iran	4.57	4.11	4.38	5.15
12	Oman	4.95	4.88	7.24	5.81	37	Tanzania	4.62	4.14	4.70	4.58
13	Chile	4.83	5.18	7.01	5.55	38	Cambodia	4.45	4.48	4.16	4.73
14	Bahrain	4.99	4.70	7.15	5.34	39	Ecuador	4.50	4.65	4.49	4.03
15	Kuwait	5.07	4.64	6.23	5.76	40	Paraguay	4.45	4.38	4.30	4.72
16	Jordan	4.88	4.75	6.72	5.14	41	Algeria	4.88	4.24	4.61	3.91
17	Russia	5.01	5.41	5.13	5.14	42	Ukraine	4.34	4.38	3.95	4.91
18	Philippines	5.02	5.28	4.31	5.99	43	Uganda	4.41	4.38	3.91	4.24
19	Brazil	5.42	5.42	4.13	5.19	44	Bolivia	4.44	4.46	3.74	3.45
20	Morocco	4.64	5.09	6.45	4.69	45	Ethiopia	4.42	4.40	3.21	3.64
21	Egypt	5.15	4.72	5.62	5.00	46	Mozambique	4.25	4.39	2.17	3.22
22	Kazakhstan	4.66	4.66	6.19	5.10	47	Venezuela	4.48	3.96	1.56	3.99
23	Uruguay	4.78	4.45	6.14	5.22	48	Angola	4.37	4.30	1.90	3.11
24	South Africa	4.81	5.00	4.99	5.01	49	Myanmar	4.44	4.27	2.04	2.79
25	Kenya	4.60	4.65	4.97	5.56	50	Libya	4.48	3.81	1.96	1.84

Table 5. Normalized Values of Decision Matrix

Rank	Country	DLO	ILO	BF	DR	Rank	Country	DLO	ILO	BF	DR
1	China	1.0000	1.0000	0.7361	0.8302	26	Pakistan	0.2156	0.1380	0.3408	0.5581
2	India	0.8981	0.6128	0.5809	1.0000	27	Peru	0.1114	0.2205	0.3873	0.4749
3	UAE	0.3199	0.3502	1.0000	0.9584	28	Colombia	0.0995	0.2138	0.3966	0.4662
4	Malaysia	0.2464	0.3485	0.8342	0.8458	29	Ghana	0.0853	0.1061	0.4562	0.5719
5	Indonesia	0.4953	0.3502	0.5584	0.7574	30	Sri Lanka	0.0569	0.1549	0.3660	0.5685
6	Saudi Arabia	0.2678	0.3249	0.8395	0.7730	31	Argentina	0.1469	0.1380	0.3554	0.4922
7	Qatar	0.3934	0.1936	0.8435	0.7868	32	Tunisia	0.0853	0.1128	0.4642	0.4419
8	Thailand	0.2038	0.3653	0.5584	0.7279	33	Lebanon	0.1327	0.1347	0.2958	0.5130
9	Mexico	0.2654	0.4226	0.4469	0.5667	34	Nigeria	0.2133	0.0976	0.2732	0.4801
10	Vietnam	0.1825	0.3737	0.5371	0.6222	35	Bangladesh	0.1825	0.1128	0.2613	0.4835
11	Turkey	0.2109	0.3182	0.5623	0.6343	36	Iran	0.0758	0.0505	0.3740	0.5737
12	Oman	0.1659	0.1801	0.7533	0.6880	37	Tanzania	0.0877	0.0556	0.4164	0.4749
13	Chile	0.1374	0.2306	0.7228	0.6430	38	Cambodia	0.0474	0.1128	0.3448	0.5009
14	Bahrain	0.1754	0.1498	0.7414	0.6066	39	Ecuador	0.0592	0.1414	0.3886	0.3795
15	Kuwait	0.1943	0.1397	0.6194	0.6794	40	Paraguay	0.0474	0.0960	0.3634	0.4991
16	Jordan	0.1493	0.1582	0.6844	0.5719	41	Algeria	0.1493	0.0724	0.4045	0.3588
17	Russia	0.1801	0.2694	0.4735	0.5719	42	Ukraine	0.0213	0.0960	0.3170	0.5321
18	Philippines	0.1825	0.2475	0.3647	0.7192	43	Uganda	0.0379	0.0960	0.3117	0.4159
19	Brazil	0.2773	0.2710	0.3408	0.5806	44	Bolivia	0.0450	0.1094	0.2891	0.2790
20	Morocco	0.0924	0.2155	0.6485	0.4939	45	Ethiopia	0.0403	0.0993	0.2188	0.3120
21	Egypt	0.2133	0.1532	0.5385	0.5477	46	Mozambique	0.0000	0.0976	0.0809	0.2392
22	Kazakhstan	0.0972	0.1431	0.6141	0.5650	47	Venezuela	0.0545	0.0253	0.0000	0.3726
23	Uruguay	0.1256	0.1077	0.6074	0.5858	48	Angola	0.0284	0.0825	0.0451	0.2201
24	South Africa	0.1327	0.2003	0.4549	0.5494	49	Myanmar	0.0450	0.0774	0.0637	0.1646
25	Kenya	0.0829	0.1414	0.4523	0.6447	50	Libya	0.0545	0.0000	0.0531	0.0000

Table 6. Correlation Coefficient

Criteria	DLO	ILO	BF	DR
DLO	**1.0000**	0.8761	0.4706	0.6684
ILO	0.8761	**1.0000**	0.5115	0.6600
BF	0.4706	0.5115	**1.0000**	0.8148
DR	0.6684	0.6600	0.8148	**1.0000**

Table 7. The Index (C)

Criteria	DLO	ILO	BF	DR
DLO	0.0000	0.1239	0.5294	0.3316
ILO	0.1239	0.0000	0.4885	0.3400
BF	0.5294	0.4885	0.0000	0.1852
DR	0.3316	0.3400	0.1852	0.0000

The final weights of the attributes was determined using Eq. [10] and are presented in Table 8.

Results Obtained from the Aggregated Weighting Method

The aggregated weights were obtained using Eq. [11]. The subjective [SWARA] weights, objective weights [CRITIC] and aggregated weights are presented in Table 9.

Table 8. Final Weights

Criteria	DLO	ILO	BF	DR
σ_J	0.1876	0.1650	0.2229	0.1902
C_J	0.1847	0.1571	0.2681	0.1629
W_J	0.2390	0.2033	0.3469	0.2108

Table 9. Results of Criteria Weights

Criteria	Subjective (SWARA)	Objective (CRITIC)	Aggregated Weighting Method
BF	0.3080	0.3469	0.3274
ILO	0.2878	0.2033	0.2455
DR	0.2197	0.2108	0.2152
DLO	0.1846	0.2390	0.2118

Business Fundamentals [BF] is the most important criterion according to both the SWARA and CRITIC methods. It is noticeable that the weights and ranks of the other criteria given by these two methods are different. Additionally, the aggregated weighting method demonstrates that BF is the most important criterion, just like the SWARA and CRITIC methods. Moreover, the weights of international logistics opportunities [ILO], digital readiness [DR] and domestic logistics opportunities [DLO] are in the same rank order as was generated using the SWARA method. However, the weights and ranks of the other criteria of the CRITIC method are not the same. Therefore, for better accuracy and reliability, aggregated weights were used in this study. The comparison of the three different weighting approaches is shown in Figure 1.

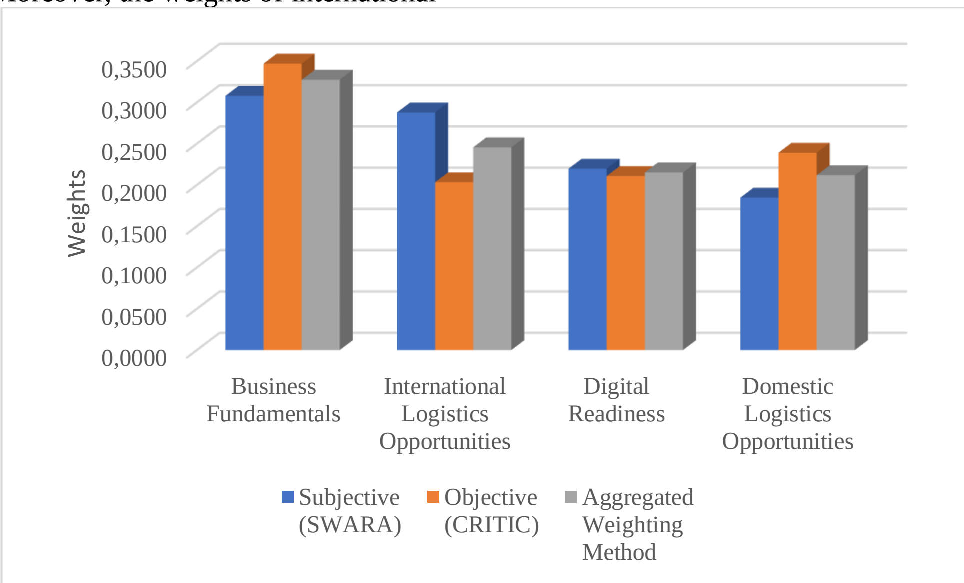

Figure 1. Results of Criteria Weights Based on Three Different Methods

According to the results obtained by the aggregated weighting method, BF and DLO are the most important and least important of the four criteria, respectively.

Results Obtained from The Ranking Method [CoCoSo]

A step-by-step calculation was conducted to obtain the rank of alternatives. First, the initial decision matrix was formed. It is shown in Table 10.

Table 10. The Initial Matrix

Weights	0.2118	0.2455	0.3274	0.2152	Weights	0.2118	0.2455	0.3274	0.2152
Optimal Value	*Max*	*Max*	*Max*	*Max*	**Optimal Value**	*Max*	*Max*	*Max*	*Max*
Country	**DLO**	**ILO**	**BF**	**DR**	**Country**	**DLO**	**ILO**	**BF**	**DR**
China	8.47	9.75	7.11	6.63	Pakistan	5.16	4.63	4.13	5.06
India	8.04	7.45	5.94	7.61	Peru	4.72	5.12	4.48	4.58
UAE	5.60	5.89	9.10	7.37	Colombia	4.67	5.08	4.55	4.53
Malaysia	5.29	5.88	7.85	6.72	Ghana	4.61	4.44	5.00	5.14
Indonesia	6.34	5.89	5.77	6.21	Sri Lanka	4.49	4.73	4.32	5.12
Saudi Arabia	5.38	5.74	7.89	6.30	Argentina	4.87	4.63	4.24	4.68
Qatar	5.91	4.96	7.92	6.38	Tunisia	4.61	4.48	5.06	4.39
Thailand	5.11	5.98	5.77	6.04	Lebanon	4.81	4.61	3.79	4.8
Mexico	5.37	6.32	4.93	5.11	Nigeria	5.15	4.39	3.62	4.61
Vietnam	5.02	6.03	5.61	5.43	Bangladesh	5.02	4.48	3.53	4.63
Turkey	5.14	5.70	5.80	5.50	Iran	4.57	4.11	4.38	5.15
Oman	4.95	4.88	7.24	5.81	Tanzania	4.62	4.14	4.70	4.58
Chile	4.83	5.18	7.01	5.55	Cambodia	4.45	4.48	4.16	4.73
Bahrain	4.99	4.70	7.15	5.34	Ecuador	4.50	4.65	4.49	4.03
Kuwait	5.07	4.64	6.23	5.76	Paraguay	4.45	4.38	4.30	4.72
Jordan	4.88	4.75	6.72	5.14	Algeria	4.88	4.24	4.61	3.91
Russia	5.01	5.41	5.13	5.14	Ukraine	4.34	4.38	3.95	4.91
Philippines	5.02	5.28	4.31	5.99	Uganda	4.41	4.38	3.91	4.24
Brazil	5.42	5.42	4.13	5.19	Bolivia	4.44	4.46	3.74	3.45
Morocco	4.64	5.09	6.45	4.69	Ethiopia	4.42	4.40	3.21	3.64
Egypt	5.15	4.72	5.62	5.00	Mozambique	4.25	4.39	2.17	3.22
Kazakhstan	4.66	4.66	6.19	5.10	Venezuela	4.48	3.96	1.56	3.99
Uruguay	4.78	4.45	6.14	5.22	Angola	4.37	4.30	1.90	3.11
South Africa	4.81	5.00	4.99	5.01	Myanmar	4.44	4.27	2.04	2.79
Kenya	4.60	4.65	4.97	5.56	Libya	4.48	3.81	1.96	1.84

The normalized values of the decision matrix were computed based on Eq. [12] and are presented in Table 11.

The total of the weighted comparability sequence, the whole of the power weight of comparability sequences for each alternative sum of the weighted comparability sequence, and the power weight of comparability sequences for each alternative, S_i and P_i, were calculated using Eqs. [14] and [15], and are shown in Table 12 and 13, respectively.

Table 11. The Normalized Matrix

Country	DLO	ILO	BF	DR	Country	DLO	ILO	BF	DR
China	1.0000	1.0000	0.7361	0.8302	Pakistan	0.2156	0.1380	0.3408	0.5581
India	0.8981	0.6128	0.5809	1.0000	Peru	0.1114	0.2205	0.3873	0.4749
UAE	0.3199	0.3502	1.0000	0.9584	Colombia	0.0995	0.2138	0.3966	0.4662
Malaysia	0.2464	0.3485	0.8342	0.8458	Ghana	0.0853	0.1061	0.4562	0.5719
Indonesia	0.4953	0.3502	0.5584	0.7574	Sri Lanka	0.0569	0.1549	0.3660	0.5685
Saudi Arabia	0.2678	0.3249	0.8395	0.7730	Argentina	0.1469	0.1380	0.3554	0.4922
Qatar	0.3934	0.1936	0.8435	0.7868	Tunisia	0.0853	0.1128	0.4642	0.4419
Thailand	0.2038	0.3653	0.5584	0.7279	Lebanon	0.1327	0.1347	0.2958	0.5130
Mexico	0.2654	0.4226	0.4469	0.5667	Nigeria	0.2133	0.0976	0.2732	0.4801
Vietnam	0.1825	0.3737	0.5371	0.6222	Bangladesh	0.1825	0.1128	0.2613	0.4835
Turkey	0.2109	0.3182	0.5623	0.6343	Iran	0.0758	0.0505	0.3740	0.5737
Oman	0.1659	0.1801	0.7533	0.6880	Tanzania	0.0877	0.0556	0.4164	0.4749
Chile	0.1374	0.2306	0.7228	0.6430	Cambodia	0.0474	0.1128	0.3448	0.5009
Bahrain	0.1754	0.1498	0.7414	0.6066	Ecuador	0.0592	0.1414	0.3886	0.3795
Kuwait	0.1943	0.1397	0.6194	0.6794	Paraguay	0.0474	0.0960	0.3634	0.4991
Jordan	0.1493	0.1582	0.6844	0.5719	Algeria	0.1493	0.0724	0.4045	0.3588
Russia	0.1801	0.2694	0.4735	0.5719	Ukraine	0.0213	0.0960	0.3170	0.5321
Philippines	0.1825	0.2475	0.3647	0.7192	Uganda	0.0379	0.0960	0.3117	0.4159
Brazil	0.2773	0.2710	0.3408	0.5806	Bolivia	0.0450	0.1094	0.2891	0.2790
Morocco	0.0924	0.2155	0.6485	0.4939	Ethiopia	0.0403	0.0993	0.2188	0.3120
Egypt	0.2133	0.1532	0.5385	0.5477	Mozambique	0.0000	0.0976	0.0809	0.2392
Kazakhstan	0.0972	0.1431	0.6141	0.5650	Venezuela	0.0545	0.0253	0.0000	0.3726
Uruguay	0.1256	0.1077	0.6074	0.5858	Angola	0.0284	0.0825	0.0451	0.2201
South Africa	0.1327	0.2003	0.4549	0.5494	Myanmar	0.0450	0.0774	0.0637	0.1646
Kenya	0.0829	0.1414	0.4523	0.6447	Libya	0.0545	0.0000	0.0531	0.0000

Table 12. Weighted Comparability Sequence and S_i

Country	DLO	ILO	BF	DR	S_i	Country	DLO	ILO	BF	DR	S_i
China	0.2118	0.2455	0.2410	0.1787	0.8770	Pakistan	0.0457	0.0339	0.1116	0.1201	0.3113
India	0.1902	0.1505	0.1902	0.2152	0.7461	Peru	0.0236	0.0541	0.1268	0.1022	0.3068
UAE	0.0678	0.0860	0.3274	0.2063	0.6875	Colombia	0.0211	0.0525	0.1298	0.1003	0.3038
Malaysia	0.0522	0.0856	0.2732	0.1820	0.5929	Ghana	0.0181	0.0260	0.1494	0.1231	0.3166
Indonesia	0.1049	0.0860	0.1828	0.1630	0.5367	Sri Lanka	0.0120	0.0380	0.1199	0.1223	0.2923
Saudi Arabia	0.0567	0.0798	0.2749	0.1664	0.5778	Argentina	0.0311	0.0339	0.1164	0.1059	0.2873
Qatar	0.0833	0.0475	0.2762	0.1693	0.5764	Tunisia	0.0181	0.0277	0.1520	0.0951	0.2929
Thailand	0.0432	0.0897	0.1828	0.1567	0.4724	Lebanon	0.0281	0.0331	0.0968	0.1104	0.2684
Mexico	0.0562	0.1037	0.1464	0.1220	0.4283	Nigeria	0.0452	0.0240	0.0895	0.1033	0.2619
Vietnam	0.0386	0.0918	0.1759	0.1339	0.4402	Bangladesh	0.0386	0.0277	0.0856	0.1041	0.2560
Turkey	0.0447	0.0781	0.1841	0.1365	0.4434	Iran	0.0161	0.0124	0.1225	0.1235	0.2744
Oman	0.0351	0.0442	0.2467	0.1481	0.4741	Tanzania	0.0186	0.0136	0.1364	0.1022	0.2708
Chile	0.0291	0.0566	0.2367	0.1384	0.4608	Cambodia	0.0100	0.0277	0.1129	0.1078	0.2584
Bahrain	0.0371	0.0368	0.2428	0.1306	0.4472	Ecuador	0.0125	0.0347	0.1272	0.0817	0.2562

Kuwait	0.0412	0.0343	0.2028	0.1462	0.4245	Paraguay	0.0100	0.0236	0.1190	0.1074	0.2600
Jordan	0.0316	0.0389	0.2241	0.1231	0.4177	Algeria	0.0316	0.0178	0.1325	0.0772	0.2591
Russia	0.0381	0.0661	0.1550	0.1231	0.3824	Ukraine	0.0045	0.0236	0.1038	0.1145	0.2464
Philippines	0.0386	0.0608	0.1194	0.1548	0.3736	Uganda	0.0080	0.0236	0.1021	0.0895	0.2232
Brazil	0.0587	0.0665	0.1116	0.1250	0.3618	Bolivia	0.0095	0.0269	0.0947	0.0601	0.1911
Morocco	0.0196	0.0529	0.2124	0.1063	0.3912	Ethiopia	0.0085	0.0244	0.0717	0.0671	0.1717
Egypt	0.0452	0.0376	0.1763	0.1179	0.3770	Mozambique	0.0000	0.0240	0.0265	0.0515	0.1019
Kazakhstan	0.0206	0.0351	0.2011	0.1216	0.3784	Venezuela	0.0115	0.0062	0.0000	0.0802	0.0979
Uruguay	0.0266	0.0265	0.1989	0.1261	0.3780	Angola	0.0060	0.0203	0.0148	0.0474	0.0884
South Africa	0.0281	0.0492	0.1490	0.1182	0.3445	Myanmar	0.0095	0.0190	0.0208	0.0354	0.0848
Kenya	0.0176	0.0347	0.1481	0.1388	0.3391	Libya	0.0115	0.0000	0.0174	0.0000	0.0289

Table 13. Exponentially Weighted Comparability Sequence and P_i

Country	**DLO**	**ILO**	**BF**	**DR**	P_i	**Country**	**DLO**	**ILO**	**BF**	**DR**	P_i
China	1.0000	1.0000	0.9045	0.9607	3.8653	Pakistan	0.7226	0.6150	0.7030	0.8820	2.9225
India	0.9775	0.8867	0.8371	1.0000	3.7013	Peru	0.6282	0.6899	0.7330	0.8519	2.9030
UAE	0.7855	0.7729	1.0000	0.9909	3.5493	Colombia	0.6134	0.6847	0.7387	0.8485	2.8854
Malaysia	0.7433	0.7720	0.9424	0.9646	3.4222	Ghana	0.5937	0.5764	0.7734	0.8867	2.8302
Indonesia	0.8617	0.7729	0.8263	0.9419	3.4028	Sri Lanka	0.5449	0.6326	0.7196	0.8855	2.7826
Saudi Arabia	0.7565	0.7588	0.9443	0.9461	3.4057	Argentina	0.6662	0.6150	0.7127	0.8585	2.8523
Qatar	0.8207	0.6682	0.9458	0.9497	3.3844	Tunisia	0.5937	0.5852	0.7778	0.8388	2.7955
Thailand	0.7140	0.7810	0.8263	0.9339	3.2551	Lebanon	0.6520	0.6113	0.6711	0.8662	2.8005
Mexico	0.7551	0.8094	0.7682	0.8849	3.2176	Nigeria	0.7209	0.5648	0.6539	0.8539	2.7935
Vietnam	0.6975	0.7853	0.8159	0.9029	3.2016	Bangladesh	0.6975	0.5852	0.6444	0.8552	2.7823
Turkey	0.7192	0.7549	0.8282	0.9067	3.2090	Iran	0.5791	0.4804	0.7247	0.8873	2.6715
Oman	0.6835	0.6565	0.9114	0.9227	3.1741	Tanzania	0.5972	0.4918	0.7506	0.8519	2.6915
Chile	0.6568	0.6976	0.8992	0.9093	3.1629	Cambodia	0.5242	0.5852	0.7057	0.8617	2.6768
Bahrain	0.6916	0.6275	0.9067	0.8980	3.1237	Ecuador	0.5496	0.6186	0.7338	0.8118	2.7138
Kuwait	0.7068	0.6168	0.8548	0.9202	3.0986	Paraguay	0.5242	0.5624	0.7179	0.8611	2.6656
Jordan	0.6684	0.6359	0.8832	0.8867	3.0743	Algeria	0.6684	0.5248	0.7435	0.8020	2.7388
Russia	0.6955	0.7247	0.7828	0.8867	3.0897	Ukraine	0.4427	0.5624	0.6865	0.8730	2.5646
Philippines	0.6975	0.7097	0.7187	0.9315	3.0574	Uganda	0.5000	0.5624	0.6827	0.8280	2.5731
Brazil	0.7621	0.7258	0.7030	0.8896	3.0804	Bolivia	0.5186	0.5809	0.6661	0.7598	2.5253
Morocco	0.6039	0.6860	0.8678	0.8591	3.0168	Ethiopia	0.5065	0.5672	0.6080	0.7782	2.4600
Egypt	0.7209	0.6309	0.8165	0.8785	3.0468	Mozambique	0.0000	0.5648	0.4390	0.7350	1.7388
Kazakhstan	0.6103	0.6204	0.8524	0.8844	2.9675	Venezuela	0.5400	0.4053	0.0000	0.8086	1.7538
Uruguay	0.6444	0.5787	0.8494	0.8913	2.9637	Angola	0.4705	0.5419	0.3625	0.7220	2.0969
South Africa	0.6520	0.6739	0.7727	0.8791	2.9775	Myanmar	0.5186	0.5336	0.4058	0.6782	2.1362
Kenya	0.5902	0.6186	0.7712	0.9099	2.8898	Libya	0.5400	0.0000	0.3823	0.0000	0.9223

The relative weights of the alternatives were computed with three appraisal score strategies using Eqs. [16]-[18], respectively. The final ranking of alternatives (based on k_i values) was determined using Eq. [19] and is presented in Table 14.

Table 14. Final Aggregation and CoCoSo Ranking

Country	k_{ia}	Ranks	k_{ib}	Ranks	k_{ic}	Ranks	k_i	Final Ranks
China	0.0294	1	34.5224	1	1.0000	1	12.8557	1
India	0.0276	2	29.8173	2	0.9378	2	11.1780	2
UAE	0.0263	3	27.6236	3	0.8934	3	10.3800	3
Malaysia	0.0249	4	24.2175	4	0.8467	4	9.1623	4
Indonesia	0.0244	7	22.2514	7	0.8307	7	8.4694	7
Saudi Arabia	0.0247	5	23.6739	5	0.8400	5	8.9686	5
Qatar	0.0246	6	23.6040	6	0.8352	6	8.9399	6
Thailand	0.0231	8	19.8656	8	0.7860	8	7.6036	8
Mexico	0.0226	11	18.3009	14	0.7688	11	7.0467	14
Vietnam	0.0226	12	18.6955	13	0.7679	12	7.1823	13
Turkey	0.0227	9	18.8158	12	0.7702	9	7.2260	11
Oman	0.0226	10	19.8387	9	0.7693	10	7.5784	9
Chile	0.0225	13	19.3662	10	0.7641	13	7.4104	10
Bahrain	0.0221	14	18.8547	11	0.7530	14	7.2232	12
Kuwait	0.0218	15	18.0406	15	0.7429	15	6.9325	15
Jordan	0.0217	16	17.7777	16	0.7363	16	6.8355	16
Russia	0.0215	17	16.5756	18	0.7322	17	6.4157	18
Philippines	0.0213	19	16.2371	22	0.7235	19	6.2905	22
Brazil	0.0213	18	15.8540	23	0.7259	18	6.1600	23
Morocco	0.0211	21	16.7989	17	0.7186	21	6.4805	17
Egypt	0.0212	20	16.3410	19	0.7220	20	6.3251	19
Kazakhstan	0.0207	22	16.3038	20	0.7055	22	6.2970	20
Uruguay	0.0207	23	16.2875	21	0.7047	23	6.2906	21
South Africa	0.0206	24	15.1427	24	0.7005	24	5.8903	24
Kenya	0.0200	26	14.8622	25	0.6809	26	5.7751	25
Pakistan	0.0201	25	13.9345	27	0.6819	25	5.4543	27
Peru	0.0199	27	13.7565	28	0.6768	27	5.3879	28
Colombia	0.0198	28	13.6340	29	0.6725	28	5.3414	29
Ghana	0.0195	29	14.0180	26	0.6636	29	5.4666	26
Sri Lanka	0.0191	32	13.1255	31	0.6484	32	5.1431	31
Argentina	0.0195	30	13.0300	32	0.6621	30	5.1223	32
Tunisia	0.0192	31	13.1602	30	0.6513	31	5.1577	30
Lebanon	0.0190	33	12.3200	34	0.6471	33	4.8621	33
Nigeria	0.0189	34	12.0877	36	0.6443	34	4.7787	36
Bangladesh	0.0188	35	11.8691	39	0.6407	35	4.6995	38
Iran	0.0183	39	12.3864	33	0.6212	39	4.8619	34
Tanzania	0.0184	38	12.2831	35	0.6247	38	4.8291	35
Cambodia	0.0182	40	11.8406	40	0.6190	40	4.6702	40
Ecuador	0.0184	37	11.8031	41	0.6263	37	4.6637	41
Paraguay	0.0181	41	11.8829	38	0.6169	41	4.6831	39
Algeria	0.0186	36	11.9291	37	0.6322	36	4.7128	37
Ukraine	0.0174	42	11.3018	42	0.5927	42	4.4594	42
Uganda	0.0173	43	10.5081	43	0.5896	43	4.1804	43

Bolivia	0.0168	44	9.3483	44	0.5728	44	3.7611	44
Ethiopia	0.0163	45	8.6061	45	0.5549	45	3.4863	45
Mozambique	0.0114	49	5.4109	46	0.3882	49	2.2252	48
Venezuela	0.0115	48	5.2889	48	0.3905	48	2.1843	49
Angola	0.0136	47	5.3314	47	0.4608	47	2.2569	46
Myanmar	0.0138	46	5.2501	49	0.4683	46	2.2343	47
Libya	0.0059	50	2.0000	50	0.2006	50	0.8687	50

According to the results, China, India, the UAE, Malaysia, and Saudi Arabia have the best logistics market performance, while Angola, Myanmar, Mozambique, Venezuela, and Libya have the worst logistics market performance.

Sensitivity Analysis

The results of this study were validated by sensitivity analysis. The sensitivity analysis was conducted by modifying the λ value. Namely, the sensitivity of the alternatives was tested to understand which alternatives are most sensitive to a change in the λ value. Table 15 illustrates the various scenarios with different λ values.

Table 15. Results of the Sensitivity Analysis

Country	**λ=0.00**	**λ=0.10**	**λ=0.20**	**λ=0.30**	**λ=0.40**	**λ=0.50**	**λ=0.60**	**λ=0.70**	**λ=0.80**	**λ=0.90**	**λ=1.00**
China	1	1	1	1	1	1	1	1	1	1	1
India	2	2	2	2	2	2	2	2	2	2	2
UAE	3	3	3	3	3	3	3	3	3	3	3
Malaysia	4	4	4	4	4	4	4	4	4	4	4
Indonesia	7	7	7	7	7	7	7	7	7	7	7
Saudi Arabia	5	5	5	5	5	5	5	5	5	5	5
Qatar	6	6	6	6	6	6	6	6	6	6	6
Thailand	8	8	8	8	8	8	8	8	8	8	8
Mexico	14	14	14	14	14	14	14	14	14	14	14
Vietnam	13	13	13	13	13	13	13	13	13	13	13
Turkey	11	11	11	11	11	11	11	11	12	12	12
Oman	9	9	9	9	9	9	9	9	9	9	9
Chile	10	10	10	10	10	10	10	10	10	10	10
Bahrain	12	12	12	12	12	12	12	12	11	11	11
Kuwait	15	15	15	15	15	15	15	15	15	15	15
Jordan	16	16	16	16	16	16	16	16	16	16	16
Russia	18	18	18	18	18	18	18	18	18	18	18
Philippines	λ21	21	21	21	21	22	22	22	22	22	22
Brazil	23	23	23	23	23	23	23	23	23	23	23
Morocco	17	17	17	17	17	17	17	17	17	17	17
Egypt	19	19	19	19	19	19	19	19	19	19	19
Kazakhstan	20	20	20	20	20	20	20	20	20	20	20
Uruguay	22	22	22	22	22	21	21	21	21	21	21
South Africa	24	24	24	24	24	24	24	24	24	24	24
Kenya	25	25	25	25	25	25	25	25	25	25	25

Pakistan	27	27	27	27	27	27	27	27	27	27	27
Peru	28	28	28	28	28	28	28	28	28	28	28
Colombia	29	29	29	29	29	29	29	29	29	29	29
Ghana	26	26	26	26	26	26	26	26	26	26	26
Sri Lanka	31	31	31	31	31	31	31	31	31	31	31
Argentina	32	32	32	32	32	32	32	32	32	32	32
Tunisia	30	30	30	30	30	30	30	30	30	30	30
Lebanon	33	33	33	33	33	33	34	34	34	34	34
Nigeria	36	36	36	36	36	36	36	36	36	36	36
Bangladesh	38	38	38	38	38	38	38	38	38	38	39
Iran	34	34	34	34	34	34	33	33	33	33	33
Tanzania	35	35	35	35	35	35	35	35	35	35	35
Cambodia	40	40	40	40	40	40	40	40	40	40	40
Ecuador	41	41	41	41	41	41	41	41	41	41	41
Paraguay	39	39	39	39	39	39	39	39	39	39	38
Algeria	37	37	37	37	37	37	37	37	37	37	37
Ukraine	42	42	42	42	42	42	42	42	42	42	42
Uganda	43	43	43	43	43	43	43	43	43	43	43
Bolivia	44	44	44	44	44	44	44	44	44	44	44
Ethiopia	45	45	45	45	45	45	45	45	45	45	45
Mozambique	48	48	48	48	48	48	48	47	47	47	46
Venezuela	49	49	49	49	49	49	49	49	49	49	48
Angola	46	46	46	46	46	46	46	46	46	46	47
Myanmar	47	47	47	47	47	47	47	48	48	48	49
Libya	50	50	50	50	50	50	50	50	50	50	50

According to the sensitivity results, the top 10 ranking order of the logistics market performance of developing countries remains unchanged under all scenarios. However, the rest of the ranking order was changed by changes in the value of λ. It is remarkable that the top 10 results for logistics market performance are so robust. Additionally, the results obtained in this study were compared with the results published in the AEMLI 2023 report. The comparison of the proposed model and the AEMLI 2023 report on the basis of the top 10 countries in terms of logistics market performance is shown in Figure 2. Furthermore, all the results of comparisons between the proposed model and the AEMLI 2023 report are presented in Appendix 1.

According to the results, China, India, the UAE, and Malaysia rank in the top 4 both in the proposed model and in the AEMLI 2023 report. However, the ranking order was changed for the countries ranked fifth, sixth, seventh, ninth, and tenth. For instance, Saudi Arabia and Qatar are in fifth and sixth place in the proposed model, while Indonesia and Saudi Arabia are in fifth and sixth place in the AEMLI 2023 report. Moreover, Oman and Chile are in ninth and tenth place in the proposed model, whereas Mexico and Vietnam are in ninth and tenth place in the AEMLI 2023 report.

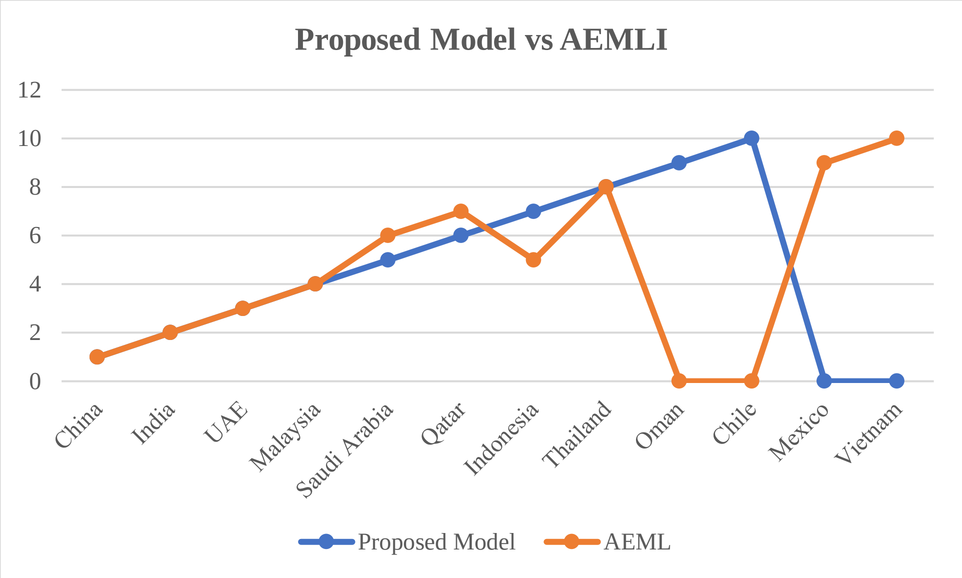

Figure 2. Comparison of the Proposed Model and the AEMLI 2023 Report

CONCLUSION

Logistics performance has become one of the most important indicators to measure the level of efficiency in international trade activity. Additionally, the growth of the logistics industry has been significant around the world due to its positive effect on the economic and social development of countries [Mešić et al., 2022]. As stated by Ozmen [2019], the evaluation of the logistics competitiveness of countries has a potential impact on the development of current policies as well as building projects for future improvement. Parallel to this, many scientists have been investigating the logistics performance of countries using different MCDM approaches. As mentioned in the literature review, most studies that evaluate logistics performance have employed LPI indicators. However, a limited number of studies have examined the logistics market performance of countries using MCDM methods. Accordingly, the main goal of this study was to assess the logistics market performance of developing countries using integrated MCDM methods. In this context, the indicators in the AEMLI report were used to assess the logistics market performance of developing countries. This index examines four key areas, namely domestic logistics opportunities [DLO], international logistics opportunities [ILO], business fundamentals [BF] and digital readiness [DR].

In the current study, a new integrated approach based on the combination of subjective [SWARA] and objective [CRITIC] weighting methods with CoCoSo has been proposed for the assessment of the logistics market performance of fifty developing countries. Two types of weighting methods were used to determine which criterion is most important for logistics market performance. For more accurate and reliable results, the aggregated weight method, which involves both objective and subjective information, was used to identify the importance of the criteria. According to the results obtained by the SWARA method, the relative importance of the criteria was as follows: BF > ILO > DR > DLO. Based on the SWARA method, the most and least important criteria were Business Fundamentals [BF] and Domestic Logistics Opportunities [DLO], respectively. According to the results obtained by the CRITIC method, the relative importance of the criteria was as follows: BF > DLO > DR > ILO. Based on the CRITIC method, the most and least important criteria were Business Fundamentals [BF] and International Logistics Opportunities [ILO], respectively. According to the results obtained by the Aggregated Weighting method, the relative importance of the criteria was as follows: BF > ILO > DR > DLO. Based on the Aggregated Weighting method, the most and least important criteria were Business Fundamentals [BF] and Domestic Logistics Opportunities [DLO], respectively.

The logistics market performance of developing countries was ranked using the CoCoSo method. According to the results obtained by the CoCoSo method, the top five developing countries in terms of logistics market performance are: China, India, the UAE, Malaysia, and Saudi Arabia. China has the best logistics market performance, followed by India and the UAE. On the other hand, the bottom five developing countries in terms of logistics market performance are: Angola, Myanmar, Mozambique, Venezuela, and Libya. Libya has the worst logistics market performance, followed by Venezuela and Mozambique.

The present findings seem to be inconsistent with those of another study [Kara et al., 2022], which found the top five countries to be the UAE, China, Malaysia, Saudi Arabia, and Qatar. There were also some differences in the bottom five countries, as that study found that Mozambique, Angola, Venezuela, Myanmar, and Libya had the worst logistics market performance. Although the results reported here differ from those of the study conducted by Kara et al. [2022], the findings are consistent with the original AEMLI 2023 report. For instance, China, India, the UAE, and Malaysia are ranked the same in both the proposed model and the AEMLI report. However, significant changes were observed in the bottom five rankings. All comparisons between the proposed model and the AEMLI report are presented in Appendix I.

In this research, a sensitivity analysis with different λ values was conducted. According to the results of the sensitivity analysis, the proposed model gives stable ranking results for logistics market performance. In other words, no significant changes in ranking were observed after modifying the λ values. Thus, it can be concluded that the proposed model is efficient and convenient for the assessment of logistics market performance by MCDM methods.

With this research, the following contributions have been made to the existing literature: [1] A new model has been proposed to evaluate the logistics market performance of countries. [2] To the best of author's knowledge, this is the first study to examine logistics market performance through the combination of two weighting methods. [3] The empirical results indicate that the proposed model has been validated by the sensitivity analysis. Therefore, it can be applied to other decision-making problems in the logistics industry.

In addition to its aforementioned contributions, the current study also has some limitations. For instance, it has only examined one time period [2022]. Therefore, the current study could be replicated over more than one time period, and the results from each period could be compared. Afterwards, more detailed research could be conducted by increasing the number of criteria and countries. Additionally, further research could be carried out with other MCDM methods, including fuzzy and gray approaches.

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Appendix 1.

Country	Proposed Model	Country	AEMLI Report	Rank Change	Country	Proposed Model	Country	AEMLI Report	Rank Change
China	1	China	1	=	Pakistan	27	Pakistan	26	▼
India	2	India	2	=	Peru	28	Peru	27	▼
UAE	3	UAE	3	=	Colombia	29	Colombia	28	▼
Malaysia	4	Malaysia	4	=	Ghana	26	Ghana	29	▲
Indonesia	7	Indonesia	5	▼	Sri Lanka	31	Sri Lanka	30	▼
Saudi Arabia	5	Saudi Arabia	6	▲	Argentina	32	Argentina	31	▼
Qatar	6	Qatar	7	▲	Tunisia	30	Tunisia	32	▲
Thailand	8	Thailand	8	=	Lebanon	33	Lebanon	33	=
Mexico	14	Mexico	9	▼	Nigeria	36	Nigeria	34	▼
Vietnam	13	Vietnam	10	▼	Bangladesh	38	Bangladesh	35	▼
Turkey	11	Turkey	11	=	Iran	34	Iran	36	▲
Oman	9	Oman	12	▲	Tanzania	35	Tanzania	37	▲
Chile	10	Chile	13	▲	Cambodia	40	Cambodia	38	▼
Bahrain	12	Bahrain	14	▲	Ecuador	41	Ecuador	39	▼
Kuwait	15	Kuwait	15	=	Paraguay	39	Paraguay	40	▲
Jordan	16	Jordan	16	=	Algeria	37	Algeria	41	▲
Russia	18	Russia	17	▼	Ukraine	42	Ukraine	42	=
Philippines	22	Philippines	18	▼	Uganda	43	Uganda	43	=
Brazil	23	Brazil	19	▼	Bolivia	44	Bolivia	44	=
Morocco	17	Morocco	20	▲	Ethiopia	45	Ethiopia	45	=
Egypt	19	Egypt	21	▲	Mozambique	48	Mozambique	46	▼
Kazakhstan	20	Kazakhstan	22	▲	Venezuela	49	Venezuela	47	▼
Uruguay	21	Uruguay	23	▲	Angola	46	Angola	48	▲
South Africa	24	South Africa	24	=	Myanmar	47	Myanmar	49	▲
Kenya	25	Kenya	25	=	Libya	50	Libya	50	=

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ORIGINAL PAPER

EXPLORING THE TREND OF THE RESEARCH ON LOGISTICS 4.0

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ABSTRACT. Background: As a result of the Industry 4.0 revolution, the Logistics 4.0 concept emerged, changed the already adopted solutions in traditional logistics, and introduced new enabling technologies. As Logistics 4.0 is a relatively new term and considering the emerging literature on these topics, the goal of this study is to identify the main research areas, understand the current state of development, and recommend potential future directions.
Methods: A bibliometric analysis of 181 scientific publications available in the Web of Science core collection database, dealing with the Logistics 4.0 research area and published between 2013 and early 2023 was performed. The analysis was carried out using VOSviewer software. Several bibliometric parameters were analyzed, such as year of publication, paper type, research area, distribution of articles by countries, language of publications, keyword and citation analysis, and most productive authors and organizations.
Results: The results of the study show that in the period from 2013 until early 2023 there were 181 publications produced on Logistics 4.0, published mostly in English, by a total of 200 authors from 41 different countries. Additionally, it was revealed that the main research areas in the field of Logistics 4.0 include supply chain visibility and transparency, IoT applications, big data analytics, AI and ML algorithms, robotics and automation technologies, blockchain technologies, and sustainability in logistics. These research areas represent key focus areas in the context of advancing logistics operations and optimizing supply chain management.
Conclusions: The results reinforce the main trends of the topic and provide an indication for future research. To the best of the authors' knowledge, this study is one of few attempts to investigate Logistics 4.0 research using a bibliometric analysis based on articles published in the past decade.

Keywords: Logistics 4.0, Industry 4.0, bibliometric analysis, VOSviewer

INTRODUCTION

Industry 4.0, also known as the fourth industrial revolution, begins to spread from 2011 in Germany, and logistics is only one small segment that has undergone numerous changes under its influence [Atzeni et al., 2021]. Under that influence, logistics has become a competitive driver for online stores and retailers around the world, where people and companies buy, produce, manage, sell, and deliver their products worldwide [Tang & Veelenturf, 2019]. The Logistics 4.0 concept describes the adoption of technologies and concepts of Industry 4.0 in the field of logistics [Lagorio et al., 2020], and the key technologies that drive Logistics 4.0 are cyber-physical systems (CPS), the Internet of Things (IoT), Big Data analytics, blockchain, and cloud computing [Angreani et al., 2020].

Amr, Ezzat, and Kassem [2019] defined the term Logistics 4.0 as: 'a strategic technological direction that integrates different types of technologies to increase both the efficiency and effectiveness of the supply chain, shifting the focus of organizations to value chains, maximizing the value delivered to the customers as well as customers by raising the levels of competitiveness. This is achieved by increasing the levels of transparency and decentralization among different parties through digitalization'. However, there is still no consensus on the definition and characteristics of the term Logistics 4.0 and digital technologies in logistics activities, which is why authors often confuse these two terms.

Some benefits of Logistics 4.0 are the implementation of self-regulating processes that

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improve supply chain transparency and achieve flexibility, process automation, decentralized decision-making, increased productivity, and cost reduction [Oleśków-Szłapka & Stachowiak, 2019]. On the other hand, the costs of implementation are very high because companies should first identify their key organizational processes and evaluate their technological needs to determine in which technology and when they should invest [Kodym et al., 2020]. Another challenge implies the collaboration of all stakeholders, which could lead to significant cost reduction [Chabot et al., 2018].

Figure 1 shows different business sectors that commonly use some technologies related to Logistics 4.0., according to the three main activities of logistics: inventory and warehouses, transportation and distribution, and supply chain.

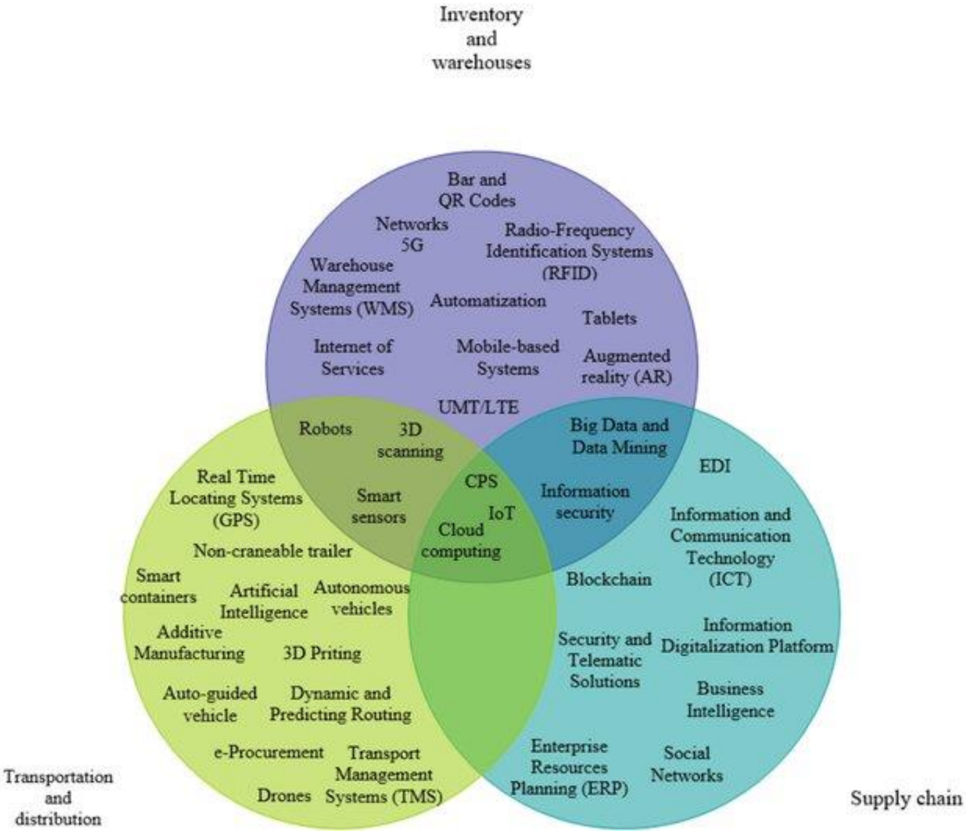

Fig. 1. Logistics 4.0 technologies grouped in the field of application
Source: Malagón-Suárez and Orjuela-Castro [2022]

For the purpose of writing this article, desk research was conducted to collect secondary data. Analysis of secondary data and scientific papers on Logistics 4.0 indicates a large gap between developed and developing countries, which have greater barriers in the adoption of Logistics 4.0 concepts due to the low level of application of technology in their supply chains. In their study, Facchini et al. [2020] proposed a maturity model for Logistics 4.0 based on Industry 4.0 implementation in logistics processes, so that companies would be in a better position to plan the next steps towards the fourth industrial revolution. Werner-Lewandowska and Kosacka-Olejnik [2019] investigated the level of Logistics 4.0 tools in the Polish service industry on a sample of 2000 enterprises.

Moreover, the desk research conducted by the authors recognizes the lack of studies focused on the bibliometric analysis of Logistics 4.0, as well as the implementation aspects of Logistics 4.0. Most publications analyze the technological aspects of Logistics 4.0 and how useful they are for the adoption of Logistics 4.0 [Khan et al., 2022]. For example, a study by Markov and Vitliemov [2020] analyzed the implementation of blockchain technologies in logistics and supply chains in the context of the automotive industry. A study by Atzeni et al. [2021] presented the results of a bibliometric analysis of

64 scientific articles whose focus is on collaborative robots ('cobots') applied to logistics systems. Bigliardi et al. [2021] conducted a bibliometric analysis on Industry 4.0 in the logistics field, based on 131 articles gathered from the Scopus database, published from 2013 to early 2020. Another recent study by Rejeb et al. [2020] analyzed and reports the 807 journal articles on the the Internet of Things indexed in the Scopus database. Another systematic literature review by Malagón-Suárez and Orjuela-Castro [2023] investigated the challenges and trends in the implementation of Logistics 4.0, based on articles published from 2015 to 2021 in the Scopus, Science Direct, Taylor and Francis and Google Scholar databases.

Due to the lack of a bibliometric analysis of publications of Logistics 4.0, the aim of this article is to provide a quantitative analysis of the academic literature on Logistics 4.0 performed on 181 scientific articles. To be more precise, the analysis takes into account the following main parameters: document type, year of publication, keywords, research area, most active countries, organization, authors (and co-authors), as well as citations. This study is unique because most previous systematic and bibliometric reviews were carried out on data retrieved from the Scopus database, and for the purpose of writing this paper the Web of Science core collection database was selected, as it is one of the most widely used databases.

The organization of the study is as follows. The first section will explain the objectives and background of the study. The second section will outline the research methodology used in this study, including the scope, source, and data collection for the analysis. The third section will include detailed and exhaustive descriptive statistics, focusing on publication output, citation analysis, distribution of documents by countries, and analysis of the most active organizations and authors. The next section will present the results and findings of the bibliometric analysis carried out on the sample of the articles reviewed, with the focus being on the frequency of keywords, co-authorship analysis, and citation metrics. Finally, the fifth section concludes the article by summarizing the significant findings and recommendations for future research.

RESEARCH METHODOLOGY

The global literature on Logistics 4.0 published between 2013 and 2023 was scanned in the WOS core collection database. The WOS was chosen because it is considered the most selective database [Singh et al., 2021], thus it is assumed that the WOS records are the highest-quality research articles, and, on the other hand, based on desk research. This type of research on Logistics 4.0 had not been performed until then, so the contribution of this article is evident. The search term applied to identify the closest matching publication included "Logistics 4.0", which was used as the keyword in the title or abstract. The information for the documents that met the threshold included the year of publication, language, journal, title, author, affiliation, keywords, document type, and citation count, all of which was exported into the CVS format. The date of retrieval was 15 May 2023. To analyze co-authorship, co-occurrence, citation, bibliographic coupling, co-citation, and themes, VOSviewer software (version 1.6.10) was used. VOSviewer is a free software tool for constructing and visualizing bibliometric networks [www.vosviewer.com].

Bibliometric analysis using a quantitative linguistic technique consisting of statistical and mathematical methods applied to sets of bibliometric references in the academic literature allows for a rigorous examination of all aspects related to publications on a particular topic [Saglietto, 2021]. It helps to determine the most influential authors, their affiliations, the keywords they use, and how academic studies are related. It consists of general descriptive statistics, such as the identification of the main authors, countries, publishing journals, or organizations [Wu & Wu, 2017]; and more sophisticated methods such as document co-citation analysis, which is among the most commonly used bibliometric techniques [Fahimnia et al., 2015; Appio et al., 2016]. The result of the study co-citation analysis is in the form of a map that consists of a set of circles representing cited documents, and a set of links representing the co-occurrence of circles in the reference list of papers upon which the map is based. Documents are co-cited if they appear together in the reference list of the publication, that is, Documents A and B are co-cited if they are both cited by a Document C [Hjørland, 2013; Ardito et al., 2019].

In order to produce the database that was the goal of this article, data on Logistics 4.0 published between 2013 and 2023 from the Web of Science collection database was sourced. The search terms applied to identify the closest matching publication included “Logistics 4.0” as the keyword in the title or abstract.

DESCRIPTIVE STATISTICS

In this section, some general descriptive statistics are made on the sample of documents reviewed, in terms of document type, year of publication, geographical distribution of the articles, research area, and most influential authors and organizations.

This first analysis will examine published documents, depending on their document types, which refer to the type of document based on the originality of the documents such as journal articles, conference proceedings, book chapters, editorial materials, etc. [Sweileh et al., 2017].

Between 2012 and early 2023, a total of 181 publications on the topic of Logistics 4.0 were identified in the WOS core collection database. These publications included 88 original research articles, 81 proceeding articles, 11 review articles, 1 book chapter and editorial material, and 12 other forms of publication (Figure 2).

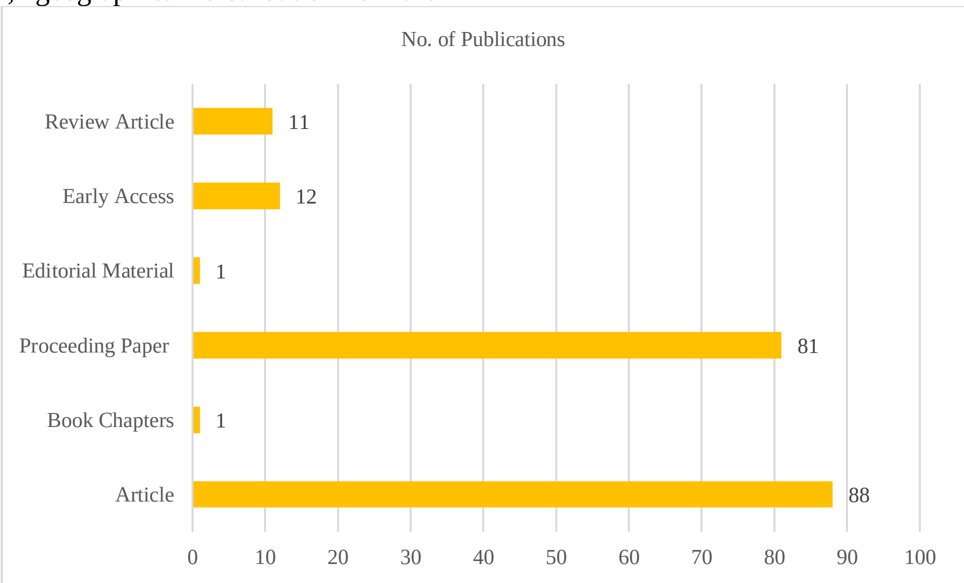

Fig. 2. Document type
Source: authors’ own work.

The published documents from the data set were also analyzed based on the number of documents published per year. According to Ahmi and Mohd Nasir [2019], the examination of documents based on the year of publication helps the researcher observe the pattern and popularity of the research subject over time. Kruckhans and Meier [2013] published the first publications on Logistics 4.0. Since then, the numbers have increased year by year, and the highest number of publications on Logistics 4.0 was in 2022 (see Figure 3). More than 80% of the studies have been published in the last five years. For 2023, only the first five months are included in the time span of the analysis, and in this period a total of 13 papers were recorded, which is why it is reasonable to expect a significant increase by the end of the year. Logistics 4.0 can be concluded to be a relatively young but very popular research field. This trend indicates the increasing importance of Logistics 4.0 not only in practice, but also in science and suggests that the application of Logistics 4.0 has become more popular in recent years. [Bigliardi et al., 2021].

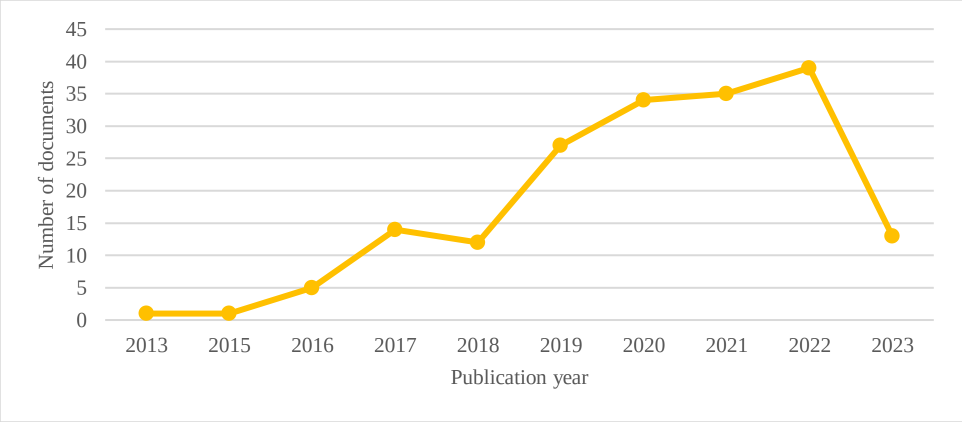

Fig.3. Publication by year
Source: authors' own work.

Almost all of the publications (178, 98.34%) were written in English and only three of them were published in German.

This section categorizes the publications based on the research area, as summarized in Figure 4. Considering that Logistics 4.0 is more focused on studies related to engineering and management, it is evident that both subject areas represent 42% (76 articles) and 24% (44 articles) of the total publications, respectively. Other contributing research areas include computer science, technology science, environmental science, materials science, transportation, chemistry, and physics.

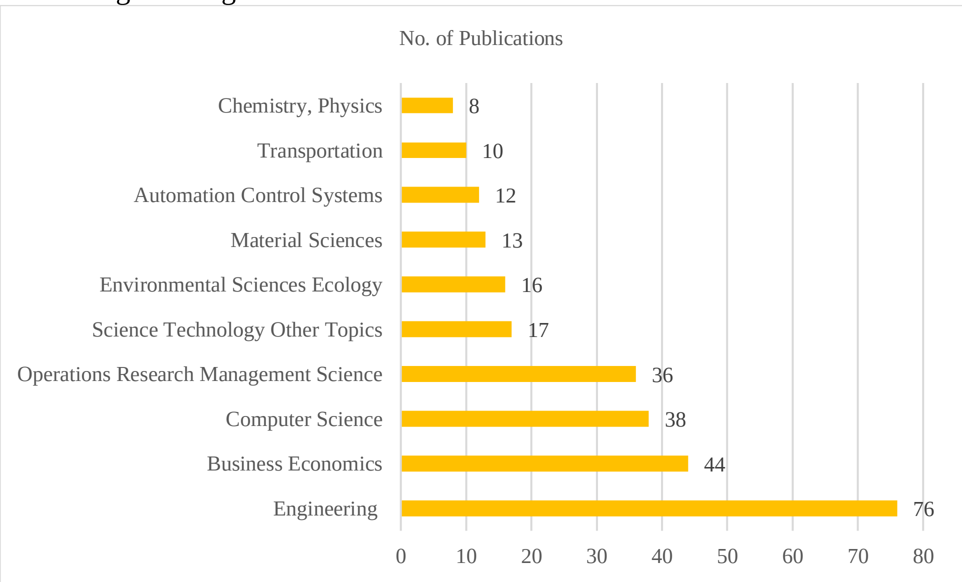

Fig. 4. Research area
Source: authors' own work.

In general, a total of 41 identified countries were involved in Logistics 4.0. The most active countries with a minimum of three publications on Logistics 4.0 are listed in Figure 5. Poland contributes the largest number of publications (27) representing 17.09% of the total publications on Logistics 4.0, followed by Germany and Italy (23, 4.96%), India (12, 2.59%), and the Czech Republic (10, 2.16%). Based on the results shown in Figure 5, it can be concluded that European countries have taken the lead in research into Logistics 4.0 compared to the rest of the world. Due to the fact that industry 4.0 started to develop in Germany in 2011 and that Germany, together with Italy and China, one of the world's productive powers, the fourth industrial revolution is still being studied more in these countries than in others.

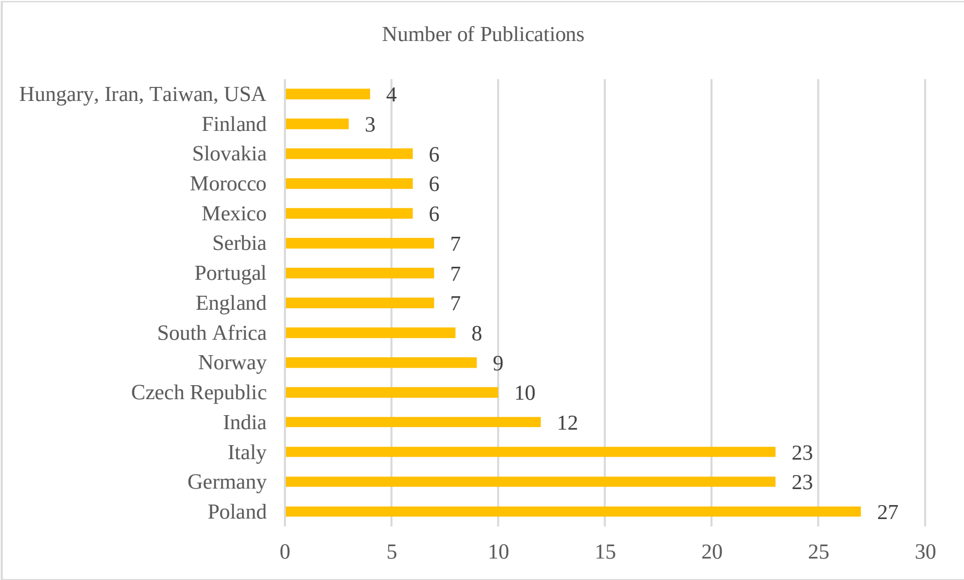

Fig. 5. Most active countries with a minimum of three publications
Source: authors' own work.

Table 1 presents the most active academic institutions contributing most to Logistics 4.0 research with a minimum of five publications. It is revealed that 200 institutions have published related papers, and eight of them have more than five publications. Poznan University of Technology in Poland has the highest number of publications on Logistics 4.0 (9, 4.97%). The University of Johannesburg (7, 3.87%) is the second highest, followed by the Norwegian University of Science Technology, the University of Bergamo and the University of West Bohemia Pilsen (6, 3.31%).

Table 1. Most active institutions with a minimum of five publications

Organization	No. of publications	Percentage (%)
Poznan University of Technology	9	4.97
University of Johannesburg	7	3.87
Norwegian University of Science Technology NTNU	6	3.31
University of Bergamo	6	3.31
University of West Bohemia Pilsen	6	3.31
Indian Institute of Technology IIT Delhi	5	2.76
Indian Institute of Technology System IIT System	5	2.76
University of Belgrade	5	2.76

Source: authors' own work.

A total of 234 authors have participated in publications on Logistics 4.0. Table 2 lists the most active authors, but to be more effective, the table is limited to the authors who have published at least three articles in the field of Logistics 4.0. Of 234 authors, only ten authors have published more than two papers in this field. Among them, C. Cimini from the University of Bergamo, A. Lagorio, also from the University of Bergamo, and Michal Zoubek from the Czech Technical University Prague have six papers, which mostly focus on smart manufacturing and logistics. In addition to these authors, J. Oleskow-Szlapka, H. Yu, G. P. Agnusdei, J. O. Strandhagen, M. Šimon, S. El Hamdi, and F. Pirola have published more than two publications on Logistics 4.0.

Table 2. The most active authors with more than two publications

Author name	No. of publications
Cimini, Chiara	6
Lagorio, Alexandra	6
Zoubek, Michal	6
Oleskow-Szlapka, Joanna	4
Yu, Hao	3
Agnusdei, Giulio Paolo	3
Strandhagen, Jan Ola	3
Šimon, Michal	3
El Hamdi, Sarah	3
Pirola, Fabiana	3

Source: authors' own work.

BIBLIOMETRIC ANALYSIS

This section describes the bibliometric analysis of co-occurrence of author keywords, co-authorship of authors, co-authorship of countries, and citation metrics. In the case of co-occurrence of author keywords, the total link strength (TLS) points to the number of publications in which any two terms appear together, and in the case of co-authorship analysis, TLS shows the number of co-authored publications with two researchers [Van Eck & Waltman, 2018].

An analysis of the author's keywords for the articles included in the review and that occurred more than twice in the WOS core collection database generated a list of 37 with a total of 242 keywords. Based on this analysis, nine clusters with different colors were obtained, as shown in Figure 6. A circle represents a keyword, and the size of the circle is proportional to the co-occurrence frequency of the keyword. The distance between two circles in the figure is determined by the density, and the larger the density, the closer the distance between two circles [Rejeb et al., 2020]. The first cluster, which is colored red, is related to digital transformation, digitalization, internal logistics, logistics 4.0, logistics performance, manufacturing, maturity, and warehouse. The second cluster, which is colored green, includes the keywords of artificial intelligence, automotive, big data, internet of things (IoT), and machine learning.

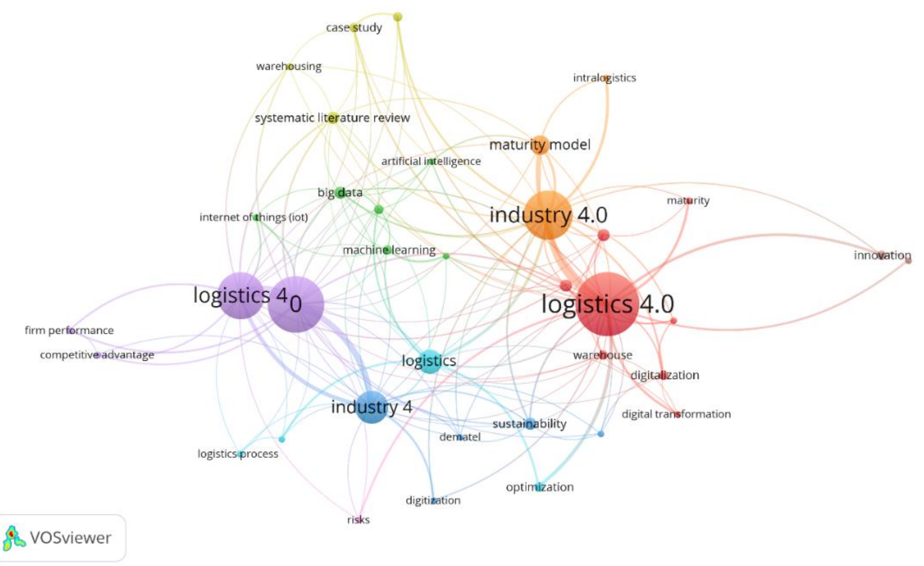

Fig. 2: Network visualization map of author keywords
Source: authors' own work.

The keywords that appeared most after exclusion of the core keywords related to a search query were industry 4.0, logistics, maturity model, and those related to the main technologies that are transforming industrial production, such as big data, manufacturing, internal logistics, warehouse, digitalization, innovation, internet of things, machine learning, etc. (see Table 3).

Table 3. The most frequently used keywords

Author Keywords	Total	Percentage (%)
logistics 4.0	29	11.98
industry 4.0	21	4.53
logistics 4	20	4.31
industry 4	13	2.80
logistics	9	1.94
maturity model	7	1.51
big data, manufacturing, sustainability, systematic literature review, internal logistics	4	0.86
warehouse, case study, digitalization, human factors, innovation, internet of things, machine learning, optimization	3	0.65

Source: authors' own work.

Figure 7 shows the network visualization map of influential authors that have more than five citations by performing a co-authorship analysis using the fractional counting method using VOSviewer. The color, circle size, font size, and thickness of connecting lines indicate the strength of the relationship amongst the authors. Connected authors, indicated by the same color, are commonly grouped together. The diagram shows that J. Oleskow-Szlapka co-authored with F. Facchini, L. Ranieri and A. Urbinati. (colored green). Moreover, M. Adamczak has collaborated with P. Cyplik, L. Hadas and A. Stachowiak (colored red), as well as R. Domanski with G. Pawlowski and H. Wojciechowski (colored blue).

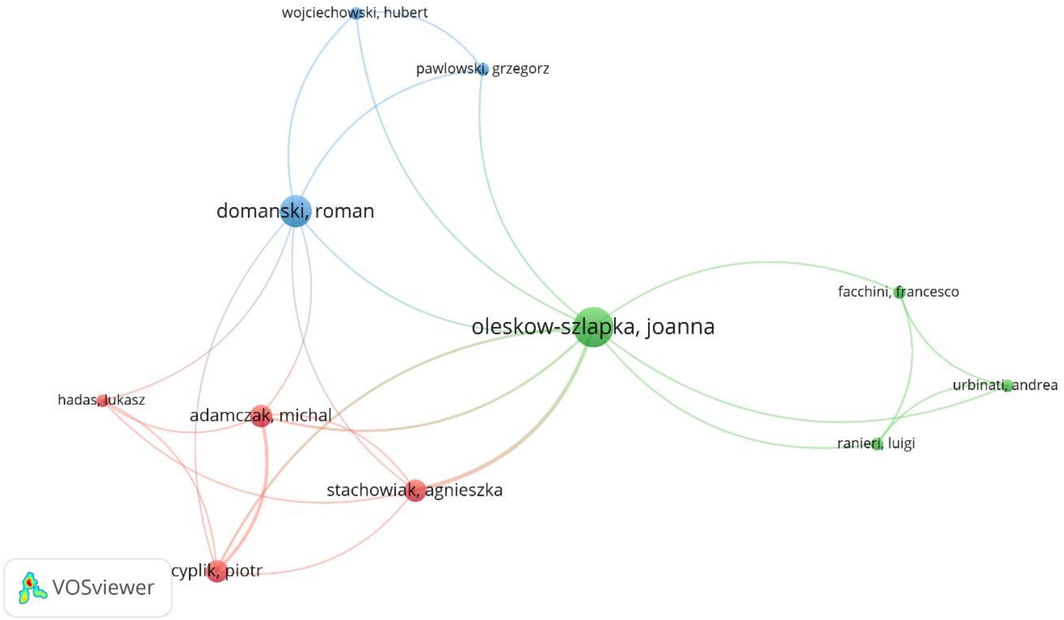

Fig. 7: Network visualization map of the co-authorship based on authors that have a minimum of five numbers of citations (fractional counting)
Source: authors' own work.

Further analysis shows the network visualization map of the authors according to the countries with which they are affiliated (Figure 8). This analysis considered only countries with more than two articles and more than five citations. Different colors represent a different clusters, and the size of the circles represents the number of publications. The thickness of the lines represents the strength of the country. As shown in Figure 8, the main partners for Poland are Italy and Serbia (colored red). Germany collaborates closely with Brazil (colored blue), while Austria works closely with Thailand and the United States of America (colored green).

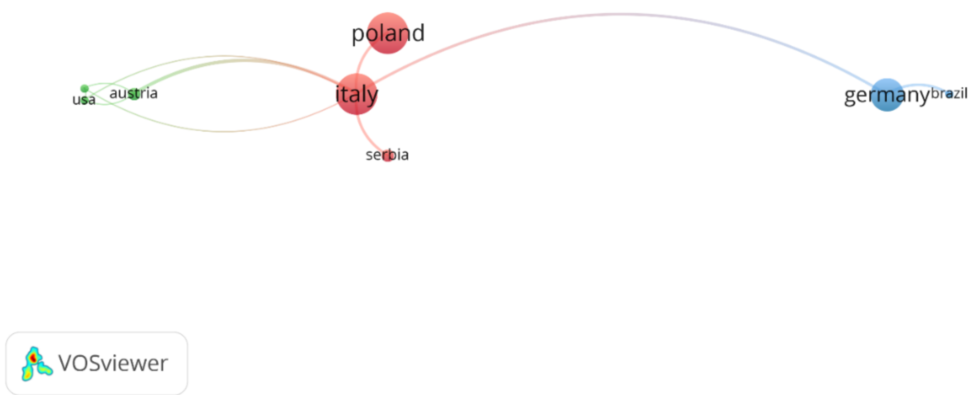

Fig. 8: Network visualization map of the co-authorship based on countries that have a minimum of two numbers of articles and five numbers of citations (fractional counting)
Source: authors' own work.

The following citation metrics show the impact of publications on Logistics 4.0. There are 181 published documents with a total of 3483 citations reported in 10 years (2013-2023) of Logistics 4.0 publications (Table 4). Additionally, there are an average of 387 citations per year and 19,24 citations per document, with a Hirsch *h*-index of 24.

Table 4. Citation metrics

Metrics	Data
Publication years	2013-2023
Citation years	10
Documents	181
Citations	3483
Citations per year	387
Citations per document	19.24
Hirsch h-index	24

Source: authors' own work.

The top ten articles most cited (based on the number of times the document was cited) in the field of Logistics 4.0 were listed in descending order of the number of citations received in Table 5. The document entitled "Industry 4.0 and the current status as well as future prospects on logistics" by Hofmann and Rusch received the highest number of citations among all the papers (749 citations or an average of 107 citations per year). The second most cited article is "Industry 4.0 implications in logistics: an overview" by Barreto, Amaral and Pereira with a total number of 280 citations or an average of 40.00 citations per year. Both articles were published in 2017. Understandably, as the peer review process requires time, for more recent publications, it is difficult to achieve a high citation rate, but it is reasonable to expect an increase of citations for papers recently published.

Table 5. The top ten most cited articles in the field of Logistics 4.0

Authors	Title	Source	Cites	Cites per year
Hofmann, E. & Rusch, M.	Industry 4.0 and the current state, as well as future prospects on logistics	Computer Science, Interdisciplinary Applications	749	107
Barreto, L., Amaral, A. & Pereira, T.	Industry 4.0 implications in logistics: an overview	Manufacturing Engineering Society International Conference 2017 (MESIC 2017)	280	40.00
Winkelhaus, S. & Grosse, E.H.	Logistics 4.0: a systematic review towards a new logistics system	International Journal of Production Research	226	45.2
Witkowski, K.	Internet of Things, Big Data, Industry 4.0-Innovative Solutions in Logistics and Supply Chains Management	7TH International Conference on Engineering, Project, and Production Management	195	27.86
Tang, C.S. & Veelenturf, L.P.	The strategic role of logistics in the industry 4.0 era	Transportation Research Part E-Logistics and Transportation Review	184	36.80
Strandhagen, J.O., Vallandingham, L.R., Fragapane, G., Strandhagen, J.W., Stangeland, A.B.H. & Sharma, N.	Logistics 4.0 and emerging sustainable business models	Advances in Manufacturing	125	17.86
Strandhagen, J.W., Alfnes, E., Strandhagen, J.O. & Vallandingham, L.R.	The fit of Industry 4.0 applications in manufacturing logistics: a multiple case study	Advances in Manufacturing	87	12.43
Bag, S., Yadav, G., Wood, L.C., Dhamija, P. & Joshi, S.	Industry 4.0 and the circular economy: Resource melioration in logistics	Resources Policy	81	20.25
Meudt, T., Metternich, J. & Abele, E.	Value stream mapping 4.0: Holistic examination of value stream and information logistics in production	CIRP Annals-Manufacturing Technology	81	11.57
Lin, C.C. & Yang, J.W.	Cost-Efficient Deployment of Fog Computing Systems at Logistics Centers in Industry 4.0	IEEE Transactions on Industrial Informatics	76	12.67

Source: authors' elaboration work.

DISCUSSION

The concept of Logistics 4.0 includes the integration of digital technologies and advanced data analytics in logistics processes to enhance operational efficiency.

As demonstrated by the analysis of keywords that appeared most in the previous chapter, the main research areas related to Logistics 4.0 include supply chain visibility and transparency, application of the Internet of Things (IoT), big data analytics, artificial intelligence and machine learning, robotics and automation, block chain technology, and sustainability.

The use of RFID technology, IoT sensors, and cloud computing platforms facilitates data collection and analysis for better visibility of the supply chain. IoT applications have transformed logistics operations by enabling seamless connectivity and real-time data exchange between physical objects and digital systems. Research in this area explores the challenges of data security, interoperability, and scalability associated with implementation of IoT in logistics [Ahmed et al., 2021]. Big data analytics in Logistics 4.0 involves the extraction, processing, and interpretation of vast datasets to gain actionable insights [Garg et al., 2021]. Research in this area focuses on developing advanced analytics and techniques, such as data mining, machine learning algorithms, and predictive modeling, to improve demand forecasting, supply chain optimization, risk management, and overall customer experience. Research on artificial intelligence (AI) and machine learning (ML) explores the use of AI-powered algorithms and ML techniques to automate logistics operations, optimize transportation routes, streamline warehouse operations, and improve demand forecasting accuracy [Younis et al., 2022; Kersten et al., 2019].

Research in the area of robotics and automation technologies focusses on the development and deployment of autonomous vehicles, drones, robotic process automation, and automated guided vehicles to handle material, order fulfilment, and inventory management [Agrawal et al., 2020; Kern, 2021]. In recent years, there has been a growing number of studies investigating the use of blockchain in supply chains, highlighting its significant potential to revolutionize various aspects of supply chain functions. This includes enhancing supply chain provenance, reengineering business processes, and bolstering security measures [Raja Santhi & Muthuswamy, 2022; Dutta et al, 2020].

All of these areas hold great potential to transform logistics operations and create new opportunities for efficiency, agility and sustainability in the context of Logistics 4.0 concept, and therefore they represent critical domains for further research. Continued research in these areas will contribute to the improvement and implementation of innovative technologies and strategies within the logistics industry.

CONCLUSION

An analysis of Logistics 4.0 research reveals many insights and makes an important contribution to the literature, highlighting the fact that the number of scientific publications in the field of Logistics 4.0 is increasing rapidly. Based on the information provided here, it can be concluded that the objective of the article has been achieved. This study provides a detailed bibliometric analysis of the Logistics 4.0 research area based on 181 studies published between 2013 and early 2023 and indexed in the WOS core collection database.

The Logistics 4.0 study, based on documents collected from the WOS core database, was initiated by Kruckhans and Meier [2013] under the title 'Industry 4.0 Fields of Action of the Digital Factory to Optimize Resource Efficiency in Production Processes'. Since then, the number of documents on Logistics 4.0 has increased rapidly, especially during the last two years, and the upward trend is likely to continue in the near future because the technology which is the basis of Logistics 4.0 has taken over the world.

More than 55% of the research papers were published as journal articles compared to other types of documents. More than 98% of the documents were published in English and originated in 41 countries. In terms of national contributions, there is a high concentration of publications from European countries, such as Poland, Germany, and Italy, with the highest number of publications (73), followed by India (12). In terms of productivity, C. Cimini, A. Lagorio, and M. Zoubek were the most productive researchers. In terms of institutional contributions, the Poznan University of Technology is the most productive institution. Logistics 4.0 is primarily focused on the fields of engineering, business economics, and computer science.

Next, based on the visualization of the keyword frequency in Logistics 4.0, the most common keywords in the documents gathered turned out to be: Industry 4.0, maturity model, big data, manufacturing, sustainability, and internal logistics. Regarding the analysis of the WOS core database on Logistics 4.0, based on ten years of publications (2013-2023), the 181 publications have registered a total of 3483 citations. Overall, there are on average 387 citations per year and 19.24 citations per article.

Additionally, this article identifies the main research areas related to the Logistics 4.0 concept, and it is worth considering the following potential future directions related to Logistics 4.0: supply chain visibility and transparency, IoT applications, Big data analytics, AI and ML algorithms, robotics and automation technologies, blockchain technologies and sustainability in logistics. These research areas represent the key focal points in advancing Logistics 4.0 and transforming traditional supply chain management into a more efficient, transparent, and sustainable ecosystem.

The publications on Logistics 4.0 were retrieved from the Web of Science core collection database and the data were analyzed objectively and comprehensively, focusing on the bibliometric network analysis shown in VOSviewer. However, this study comes with certain limitations. The first limitation of this study is that only the Web of Science core collection database was used to select the previous literature. Although the Web of Science is considered a very comprehensive database, future studies should extend the context of this study and enhance its findings by including other scientific databases, such as the Scopus database, EBSCOhost, Google Scholar, Dimensions, or any other relevant database that highlights the major contributions to guide future researchers in this field and fill in any possible gaps. Future studies could also compare the results from different databases. Secondly, no search query is completely perfect and therefore false positive and negative results should be foreseen.

However, this study has gained a broader view of the current state of Logistics 4.0 research and will provide some direction for future research, as well as identification regarding the Logistics 4.0.

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ORIGINAL PAPER

INNOVATIONS IN LAST MILE LOGISTICS - ANALYSIS OF CUSTOMER SATISFACTION WITH THE SERVICE OF DELIVERY LOGISTICS OPERATORS USING PARCEL MACHINES

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ABSTRACT. Background: The last decade of socio-economic and technological changes has brought a number of transformations in many areas. Digitization results in the transformation of an organization's business activities. Enterprises and customers have appreciated the digital world, but online transactions are not everything. It is also important to complete the transaction, which requires physical support. The CEP industry, especially its innovative solutions in the form of parcel machines, greatly assists with the demand. The aim of the article is to indicate the gradation of the significance of the components of satisfaction with the service of logistics of deliveries at the last mile stage using innovative solutions such as parcel machines on the perception and competitive position of enterprises from the CEP industry.
Methods: The information base consists of secondary and primary sources. The article uses mixed methods in the application of a parallel triangulation strategy: qualitative analysis of the existing publications, participant observation, and a nomothetic study based on the CAWI Internet survey using the Servqual methodology to assess the quality of logistics customer service.
Results: The collected material became the basis for identifying the possibilities of using the potential of customer experience for the development of enterprises, based on the structure of the signpost of the gradation of satisfaction components in the technologization of last mile deliveries in the future. The suggestions proposed by the authors can be used by scientists and managers of enterprises in the CEP industry to redefine business models based on the technology of the logistic customer service process, which should serve to increase the level of customer satisfaction.
Conclusions: The analysis of the material leads to the conclusion that the technology of customer service at the last mile stage may be insufficient in and of itself. Positive adoption, signified by the customer's satisfaction with the value obtained, is still required, i.e., "good service delivery". Such a holistic approach to technological innovation can be the key asset in the fight for customers on the CEP market.

Keywords: last mile, logistics services, technologies, innovations

INTRODUCTION

Our reality is computerized, and it seems that nothing can oppose this trend. The functioning of enterprises in these realities requires the use of modern solutions that will allow enterprises to meet the requirements of customers, but also to achieve the intended goals in relation to the activities of the competition. Moving operations to virtual space allows access to more audiences [Çipi et al. 2023; Mosescu et al. 2022], but also affects the effectiveness of the activities carried out. [Marei et al. 2023; Roman and Rusu 2022; Markic et al. 2022] In the last decade, special attention has been paid to the new opportunities that resulted from the use of the achievements of Industry 4.0. [Manavalan and Kandasamy 2022] Solutions such as blockchain [Ugochukwu et al. 2022], digital-twin [Zhang et al. 2022], augmented reality [Kettle and Lee 2022], and the Internet-of-Things [Paolone et al. 2022] have become a permanent part of the landscape of entrepreneurship in various industries and areas. They are also used in logistics, which, due to its specific service activity, must meet the requirements of various recipients - from individual consumers, through

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small and medium-sized enterprises, to global corporations. The flexibility of logistics activities has been achieved through the implementation of IT systems that currently use the solutions of the fourth industrial revolution, and for which a separate formulation has even appeared - Logistics 4.0. [Khan et al. 2022; Nour 2022]

Logistics activities have changed under the influence of the development of technology, and has also strongly influenced the availability of new technological solutions, using the synergy effect. Currently, it is difficult to imagine that logistics operations would be performed without the use of technology, especially in the global dimension. The experience of recent years (pandemic, war in Ukraine, raw materials crisis) shows that the participation of technology has become necessary to be able to meet the requirements of speed of action, security of people and goods, and resistance to various crises. The flexibility of the challenges taken is no longer extraordinary, because it is necessary to manage operations sustainably, as well as to build a logistics system resilient [Postigo Marcos et al. 2022; Al-Banna et al. 2022] to all the adversities that the world is currently facing in economic, social, or political terms.

A special area of logistics activities are CEP services (courier - express - postal services), which are designed to respond to the needs of business customers (often senders of parcels), as well as recipients (including individual consumers). The organization of such services poses many problems and limitations, and at the same time, one should remember the efficiency of one's own business activity and the costs of the company's operation. That is why the most flexible solutions are increasingly sought, which will reduce the cost of travel, handle the largest possible number of shipments and customers, lower emissions, and shorten customer service time. Hence, OOH (out-of-home) delivery solutions to collection points are becoming more and more popular. They can be divided into two groups: PUDO (pick-up and drop-off) deliveries to various collection points and APM (automated parcel machines) deliveries.

An important element of this system are the requirements and expectations of customers for whom the use of CEP industry services is of key importance in many aspects. The CEP industry, as service providers, must take into account the need to find solutions that will satisfy customers. This is a prerequisite for acquiring and retaining customers. [Sułkowski et al. 2022; Olsson et al. 2023] Interestingly, the research also indicates the need for greater emphasis on the socialization of CEP industry services, as well as in the context of technology and sustainable development. [Lauenstein and Schank 2022; Coffee and Pierański 2021]

Building a logistic customer service system for the CEP industry requires understanding the needs of both business customers and an individual approach to consumers. Of particular importance for the development of the CEP industry was the e-commerce market and customers' delight in online shopping. This challenge has completely changed the approach to creating courier services and customer service. [Hassel and Sieker 2022]

Unfortunately, the customization of services for consumers is associated with increased costs, but it also causes companies from the CEP industry to try to find innovative solutions that will meet the needs of fast order fulfillment, full availability of information, and flexibility when collecting parcels. [Schnieder et al. 2021] More and more often, a sustainable last mile service becomes a challenge, which in the perspective of customer expectations, takes on a completely new meaning. [Otter et al. 2017]

The aim of the article is to indicate the gradation of the significance of the components of satisfaction with the service of logistics of deliveries at the last mile stage using innovative solutions such as parcel machines on the perception and competitive position of enterprises from the CEP industry. The article uses mixed methods in the application of a parallel triangulation strategy: qualitative analysis of the existing publications, participant observation, and a nomothetic study based on the CAWI online survey using the Servqual methodology to assess the quality of logistics customer service.

The collected material was used to create a road map in order to build a logistic customer service system based on solutions using parcel machines. The example of Poland may indicate interesting opportunities for the development of this form of supply, and at the same time constitute a good practice for others.

Technology in logistic customer service in the light of research results

The SARS-CoV-2 pandemic has strengthened the transformation towards digitization with representation, among others, in the form of digitization of documentation circulation and mechanization of customer service processes at the last mile stage, carried out by CEP industry enterprises. The review of the literature and the reported results became the basis for the researchers to design and carry out research at the turn of 2021 and 2022.

The subject of the measurement was the assessment of the use of technological innovations in the implementation of logistics customer service processes at the last mile stage for customer choices as to delivery providers. It was also to specify the necessity of matching enterprises in the CEP industry during the SARS-CoV-2 pandemic. Obtaining the research material was possible thanks to the use of the diagnostic survey method with the "us-er-centric" CAWI (Computer Assisted Web Interview) Internet survey technique. The research tool was placed on the research platform https://ebadania.pl. The questionnaire consisted of 43 basic questions, including 14 questions based on the construction of the Rensis Likert scale and questions on the metrics.

The surveyed population consisted of e-commerce customers from Poland aged 16 and over who made purchases on the Internet in the 3 months preceding the survey. Explanatory research of a descriptive and explanatory nature, classified as fragmentary and deterministic, was carried out on a selected sample with a minimum size determined on the basis of a formula taking into account the distribution of fractions:

$$n_{min}=NP(\alpha^2\cdot f(1-f))/NP\cdot e^2+\alpha^2\cdot f(1-f)$$

where:

n_{min} - is the minimum sample size

NP – the size of the study population

α - confidence level for the results

f – fraction size

e - assumed maximum error

The basis for the calculation of the sample was the study population (NP) of Polish residents who were aged 16 and over on the 31st of December 2020 (according to the Central Statistical Office, this number was 31,811,795 people). Determining the fraction in the value of 0.814 for online buyers and 0.186 for other people was possible thanks to earlier research. [Raport 2020] Moreover, a confidence level of 0.95 and a random error of 5% were assumed. Such assumptions made it possible to perform calculations and specify the minimum sample size at the level of n_{min} 233 which, as a result of the physical collection of units using the non-random selection of typical units with the snowball technique, was exceeded, resulting in 658 completed questionnaires. The material obtained in this way was anonymized and encoded in the SPSS program (Statistical Package for Social Sciences), as well as verified and validated.

The surveyed sample was dominated by women (53.2% of the respondents) in relation to men (46.8% of the respondents). In terms of age, the smallest group consisted of people aged 16 - 24 (12.3%), and the largest group of respondents were aged 55 and over (36.0%). The dominant group was inhabitants of cities (59.9%) in relation to inhabitants of rural areas (40.1%). The analysis of the representativeness of the sample in relation to the selected characteristics was carried out on the basis of a non-parametric significance test based on the χ^2 statistics in the form:

$$\chi^2 = \sum_{i=1}^{r} \frac{(n_i - np_i)^2}{np_i}$$

where:

pi - the probability that the feature X will take a value belonging to the class “i”

npi - the number of units in the i-th range

The null hypothesis (H0) adopted was that the distributions of selected variables from the sample were consistent with the distributions characterizing the population of Polish residents aged 16 and over, and the alternative hypothesis (H1) was that there was no such consistency.

Table 1. The results of calculations on the compatibility of distributions from the sample to the population - the value of the non-parametric test χ^2.

Parameter	Sample size n	N population size	The real value of χ^2	Theoretical value of χ^2	Test result $\chi^2<\chi^2_\alpha$
Gender					
Female	350	16722685	0,103	3,841	Concordance
Male	308	15089110			
Age					
16 - 24	81	3395513	2,204	12,592	concordance
25 – 34	107	5222883			
35 – 44	127	6300861			
45 – 54	106	4975279			
55 – and above	237	11917259			
Place of accommodation					
Village	264	15359918	4,197	11,07	Concordance
City up to 20,000	70	4983795			
City from 20,000 to 49,000	72	4237100			
City from 50,000 to 99,000	60	3128500			
City from 100,000 to 199,000	63	3324500			
City over 199,000	129	7231300			

[a] α – confidence level

Source: own research.

After performing the calculations and verifying the values of the statistics, the hypotheses about the compatibility of the distributions of selected variables from the sample with the distributions of the studied population were confirmed (Table 1). In the next step, analyses of the distribution of answers to the main questions were carried out, and where it was possible, logically meaningful, and statistically significant, the hypotheses about the existence of a relationship between the variables from the main questions and the variables of the metric were verified. After verification, the variables and values were compiled in the form of contingency tables and based on the χ^2 test of independence, verification of the hypotheses about the non-existence (H0) and existence (H1) of the relationship between the variables was carried out:

$$\chi^2 = \sum_i^r \sum_j^s \frac{(n_{ij}-\tilde{n}_{ij})^2}{\tilde{n}_{ij}} : \quad \chi^2_{(r-1)\cdot(s-1)}$$

where:

n_{ij} – empirical conditional numbers resulting from the contingency table,

$\tilde{n}_{ij}$ – theoretical conditional counts that would appear in the array if the features were independent.

At the same time, Cramer's V coefficient was used to verify the hypotheses:

$$v = \sqrt{\frac{\chi^2}{n \cdot \min(r-1, k-1)}}$$

where:

V – Cramer coefficient between two variables,

χ^2 is the empirical value of the statistic obtained from the study for the pair of variables.

n – number of observations

r – number of levels of one variable

k – the number of levels of the second variable

$\min(r-1, k-1)$ – the smaller of the two (r-1) or (k-1)

In addition to the assessment of customer service using parcel machines as a representation of innovative last-mile solutions, a comparison of unweighted and weighted values, based on the arithmetic mean for the expected and perceived quality of services offered by last-mile operators, was used in accordance with the Servqual methodology. [Parasuraman, Zeithaml, Berry 1985]

The survey participants admitted that for most of them online shopping is a pleasure (71.4%). This state of affairs is influenced by many factors, especially services related to the logistics of deliveries. For the respondents, apart from the goods themselves, the method of delivery and the possibility of choosing a company offering delivery services are also important. Among the available options for sending/collecting a parcel that the respondents used during the pandemic, couriers prevailed (97%), while the alternative to delivery logistics services were pick-up/drop-off points such as a kiosk/shop/gas station/CEP branch (71.7%). The respondents admitted that, in addition to these methods, they willingly use technological solutions in the logistics of deliveries, such as parcel machines, both when sending a parcel (68.7%) and when collecting it (79.3%). Slightly more than half of the respondents (55.0%) used the option of sending parcels between parcel machines.

Table 2. Calculation results for the use of parcel machines in relation to gender, age, and place of residence - test of independence χ^2 with the strength of the relationship determined by V-Cramer.

Variants	**Gender**			**Age**			**Place of accommodation**		
	χ^{2a}	p^b	V^c	χ^2	**P**	**V**	χ^2	**p**	**V**
Shipping in parcel machine	66,191	0,001	0,318	21,908	0,001	0,182	114,570	0,001	0,417
Pickup at parcel machine	69,343	0,001	0,328	67,078	0,001	0,319	95,406	0,001	0,381
Sending between parcel machines	9,918	0,002	0,126	8,070	0,233	0,111	13,614	0,018	0,144
[a] χ^2 – test value at α=0,05 [b] p – asymptotic significance [c] Relationship strength calculated using V-Cramer									

Source: own research.

The use of parcel machines to send parcels is the domain of men (84.4%) more than women (54.9%), people aged 45-54 (83.0%), and residents of cities from 50,000 to 999,000 of people (93.3%). Similarly, men (93.5%) more often than women (66.9%) choose collecting a parcel from a parcel machine, people aged 45-54 (96.2%), and residents of cities with a population of 100,000 to 1,999,000 of people (96.8%). On the other hand, men (61.7%) slightly more often than women (49.1%) choose the option of sending parcels between machines, people aged 35 - 44 (59.1%), and residents of cities from 100 to 1999 thousand people (74.6%). The existence of the indicated relationships is confirmed by the $\chi 2$ test of independence with the strength of the relationship determined by V-Cramer (Table 2.).

Among the operators of services in the field of logistics outside the home—post office, retail outlets, and parcel machines known and used by the respondents—the most frequently mentioned are InPost (88.4%), Allegro (67.5%), DPD (62.6%), Polish Post (48.0%), and Orlen (27.7%). The parcel machines most often used by the respondents are located in the immediate vicinity, i.e., less than 500 meters from the place of residence/work (39.5%) or nearby, i.e., from 0.5 to 1 km (26.4%). Slightly more than one in ten respondents admitted that the distance to the parcel machine was over 5 km (16.4%). The vast majority of respondents go to the parcel machine on foot (62.3%). The alternative is going by car (42.9%). Most of the respondents declare that they can get to the parcel machine in less than 10 minutes (71.4%) or from 11 to 20 minutes (24.3%). In the period of 3 months preceding the survey, the most frequently chosen operator of delivery services using parcel machines was InPost (77.5%).

The respondents were asked to give a detailed assessment of the service of deliveries carried out using parcel machines by last-mile service operators. The questionnaire contained 30 statements appropriately assigned to five areas in accordance with the Servqual customer service quality survey method. The theorems are divided into two blocks. The first block referred to the expectations of the respondents regarding delivery services provided with the use of parcel machines. The second block referred to the observations of the respondents on the basis of the experience gained as a result of interacting with the service provider.

When choosing a delivery service using parcel machines, the respondents have specific expectations regarding the material dimension of the service, reliability, operator's response to customer expectations, professionalism and responsibility, and empathy, which are subject to verification. Due to the fact that InPost was the most frequently indicated parcel service operator used by the respondents in the 3 months preceding the survey, a detailed analysis was carried out for this company, which resulted in the determination of the unweighted and weighted Servqual index.

When considering individual areas of the quality of delivery services using parcel machines, it turned out that the unweighted Servqual index was (-0.39), which means an unfavorable assessment for InPost. The largest gap between expectations and perceptions resulting from the respondents' experiences is in the area of empathy (-0.53), followed by the material dimension (-0.39) and response to customer expectations (-0.38). The smallest gap level occurs for reliability (-0.33) and for professionalism and responsibility (-0.32).

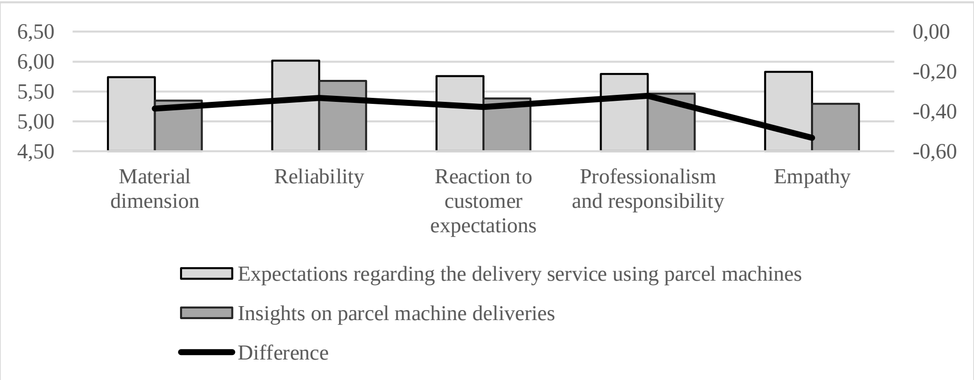

Fig. 1. The results of unweighted areas of the quality of delivery service using parcel machines using the Servqual method - for InPost (n=510). Source: own research.

However, taking into account the component of importance for the respondents of a particular area of the assessment of the quality of the delivery service using parcel machines provided by the InPost company, it turns out that the weighted Servqual index increased (-0.21). The favorable approach to zero, i.e., the state when the expected values are fully covered by the observations, was influenced by the lower importance of areas such as empathy, professionalism, and responsibility, as well as reliability in the service offered to the respondents. After adjusting for importance, although the level of vulnerabilities decreased, they are still recorded. The largest gaps were recorded for the material dimension (-0.35) and the response to customer expectations (-0.30). The next gap areas are empathy (-0.15) and reliability (-0.14). The lowest level of the gap when taking into account weighting was shown for professionalism and responsibility (-0.10).

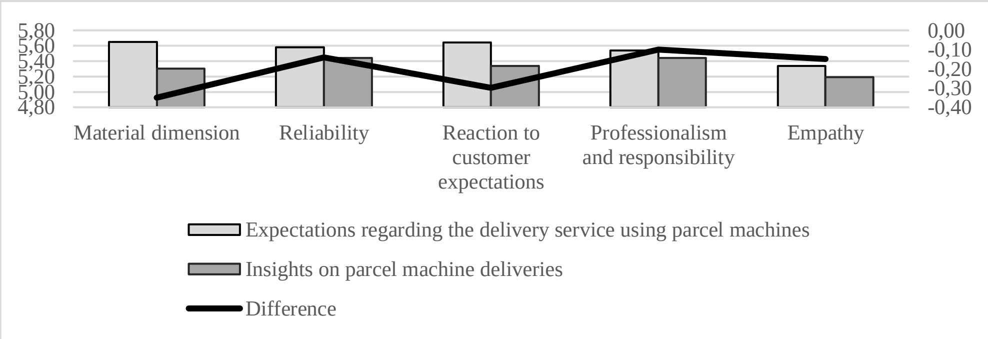

Fig. 2. The results of weighted areas of the quality of delivery service using parcel machines using the Servqual method - for InPost (n=510). Source: own work.

In detail, the InPost company within the material dimension area should work on minimizing gaps by providing lockers for bulky parcels (-074), increasing the number of parcel machines so that you do not have to wait for lockers to be released (-0.58), providing lockers for products that require low temperatures (-0.58), and variation in the size/capacity of lockers (-0.46). On the other hand, in the area of reliability, according to the respondents, detailed attention should be paid to the application for sending and receiving parcels, which should be failure-free (-0.66). In the next area of response to customer expectations, according to the respondents, the gap related to the lack of immediate assistance from the service department, which should be bridged if the customer has problems with the machine (-0.79). In terms of professionalism and responsibility, the respondents indicated gaps related to voice control for the visually impaired (-0.88) and power supply from ecological sources (-0.52), which, in their opinion, should be removed. In turn, in terms of empathy, the respondents point to a dichotomy in terms of the culture of customer service employees (-0.85), helpfulness and competence of the service department (-0.62), responding without delay to customer requests (-0.62), and lack of dedication or sufficient attention to the client (-0.51).

Table 3. The results of indications of expectations and observations in the field of delivery logistics services using parcel machines at the last mile stage.

Area	Expectations regarding the delivery service using parcel machines	Insights on parcel machine deliveries	Difference
Material dimension			
Available location of parcel machines.	6,15	5,97	-0,18
More parcel machines so you don't have to wait for the lockers to be released.	5,47	4,89	-0,58
The exterior of the parcel machine blends in with its surroundings.	5,03	4,75	-0,28
Various sizes/capacity of lockers available.	5,96	5,5	-0,46
Clean and aesthetic appearance of the compartments of the parcel machine.	5,78	5,65	-0,13
Available height of various sizes of lockers for people with difficulties.	5,78	5,65	-0,13
Special compartments for products requiring low temperatures.	5,75	5,17	-0,58

Special lockers for bulky shipments.	5,95	5,21	-0,74
Reliability			
The delivery time to the parcel locker should be in accordance with the information provided by the operator.	6,12	5,98	-0,14
The application for parcel delivery and collection services should provide information about the progress of the service in real time.	5,95	5,78	-0,17
The application for sending and receiving the parcel should be failure-free.	6,09	5,43	-0,66
Parcel machines should not expose the shipment to damage (physical/chemical), leading to the loss of properties of the contents of the shipment.	5,91	5,57	-0,34
Parcel machines should be failure-free.	5,99	5,63	-0,36
Reaction to customer expectations			
Communication with the parcel machine service should be possible using multiple channels (application, telephone, SMS) at every stage: delivery and collection.	5,84	5,61	-0,23
At each stage of the service, the customer has the opportunity to obtain detailed information regarding the delivery by contacting the Customer Service Department.	5,83	5,4	-0,43
In case of problems with the parcel machine, immediate assistance from the service department should be provided.	5,98	5,19	-0,79
From the application level, it should be possible to change the location of the parcel pick-up.	5,53	5,17	-0,36
Delivery to a parcel machine should be shorter than via other forms of delivery.	5,61	5,53	-0,08
Professionalism and responsibility			
The procedure for sending and receiving a parcel should be simple (intuitive).	5,95	5,91	-0,04
The parcel machine should be associated with the application (location, sending, tracking, receiving).	5,91	5,85	-0,06
The parcel machine should be controlled by an application without the need to use a panel placed in the machine.	5,73	5,62	-0,11
The parcel machine should be able to be voice controlled for the visually impaired.	5,82	4,94	-0,88
The parcel machine should be powered by energy from ecological sources.	5,53	5,01	-0,52
Empathy			
Customer support in the form of support should be available 7 days a week / 24 hours. per day.	5,49	5,18	-0,31
The service should react without undue delay after the customer's notification.	5,89	5,27	-0,62
Employees of the customer service department should be characterized by high personal culture.	5,98	5,13	-0,85
Customer support should be knowledgeable and helpful.	5,96	5,34	-0,62
Each customer should be given as much time as they need.	5,85	5,34	-0,51
Customer service employees should be committed to solving the problem reported by the customer.	5,78	5,41	-0,37
Customer service support should be nice and polite.	5,83	5,38	-0,45
[a] α – confidence level			

Source: own research.

Despite the imperfections noticed by the respondents in the provision of services on the example of the InPost company, in general, respondents during the SARS-CoV-2 pandemic willingly used parcel machines mainly due to flexibility in choosing the place of delivery (98.2%), saving time (94 .8%) and efficiency of delivery and collection (94.8%), competitive prices of the service (91.5%), and security of supply (85.7%). In addition, respondents believe that parcel deliveries are safe for individual customers, which is reflected in health care (63.8%), care for the shipment itself (70.2%), and payment protection (69.6%) not only during the pandemic.

Due to the experience gained during the pandemic, the diversity of the offer, and the availability of e-commerce formats, the majority of respondents believe that in the future, the demand for online shopping will increase (94.2%) and the interest in shopping in traditional stores will decrease (64.5%). The respondents also believe that in the future, buyers will be more willing to choose deliveries based on innovative last-mile logistics solutions, including parcel machines (74.5%) rather than using other forms (e.g., couriers).

DISCUSSION

The conducted research indicates the significant popularity of parcel machines among customers. Their satisfaction with the use of machines is at a high level. Given the growing popularity of this type of solution, researchers do not often undertake this topic. Most of the research, however, is conducted from the perspective of companies that are trying to find the best algorithm to determine the location of parcel machines. [Schwerdfeger and Boysen 2020; Luo et al. 2022] Other researchers also focused on social aspects, mainly related to the environmental performance of parcel machines. [Moroz and Polkowski 2016; Bonomi et al. 2022] However, looking at one of the few studies conducted in Poland [Lemke et al. 2016], similarities can be found and seems to confirm the thesis that parcel machines will be increasingly chosen by customers, especially when using online stores.

CONCLUDING REMARKS

Summing up, in view of the inertia of technology in all manifestations of human activity, one cannot remain indifferent to what concerns every human being. Each person needs a variety of resources to function. Their offer is increasingly moving from the real world to the virtual one. However, the digitization of the shopping experience finds its finalization in the analog reality. Last mile logistics in the field of deliveries is increasingly carried out using innovative forms, including parcel machines. Delivery logistics services are undergoing transformation.

However, the limitations of the presented study are significant. First, the study concerned customers on the Polish market, and it may be worth considering a comparison with other European countries. In addition, it is also worth repeating the study due to the large impact of the pandemic on customers' purchasing decisions. Thanks to the next edition of the study, it will be possible to check whether these decisions have changed over time.

The analysis of scientific and research achievements indicates the progressive technologicalization of customer service processes. The number of enterprises entering the OOH market is increasing. Reports indicate a growing number of machines. The SARS-CoV-2 pandemic has increased the momentum of the industry's development. Time will tell how long the transformation process will last. It is important to note that the ubiquitous technology should work for the benefit of people—participants of the process. Therefore, enterprises operating on the OOH market should, in the spirit of continuous improvement, take into account the opinions and suggestions of customers. Machine users, although they appreciate the advantages of the autonomy of deliveries, also point to the shortcomings recorded in the form of competence gaps that need to be filled. Without this, it may turn out that admiration for one's own development may contribute to the collapse of the current giants of the CEP industry. The future belongs to the brave and persistent, able to take up challenges and skillfully manage changes, and the current technological innovations in the CEP industry on the OOH market are certainly not the last.

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ORIGINAL PAPER

A STUDY OF MACROECONOMIC AND GEOPOLITICAL INFLUENCES AND SECURITY RISKS IN SUPPLY CHAINS IN TIMES OF DISRUPTIONS

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ABSTRACT. Background: The effect of macroeconomic and geopolitical disturbances affects the safety of logistics chains in the environment of their operation. Determining the parameters of the security of the logistics chain in the period of disruption is considered an important economic problem due to the growing threats to the economic security of the country and, in particular, to the security of the logistics sector. Supply chains in Ukraine were initially disrupted due to the COVID pandemic and then the Russian invasion. These two major disruptions have had a significant impact on logistics in Ukraine, which is why this article aims to explore their impact on supply chain operations.
Methods: The research comprises four main components: a bibliometric analysis employing the systematic literature review method, a statistical analysis of key macroeconomic indicators affecting the logistics sector in Ukraine and the global economy, survey research involving participants in supply chains, and a conclusion drawn from the analyses, addressing risks for the security of the supply chain environment. The bibliometric analysis aims to understand research trends and developments in the field, while the statistical analysis provides insights into economic factors impacting supply chains. The survey research offers valuable input from supply chain participants, contributing to a comprehensive understanding of their experiences. Finally, the conclusion draws implications from the analyses, identifying potential risks and proposing measures to enhance supply chain resilience and security.
Results: The research results indicate that the disturbances analyzed not only affected the fluctuations of global GDP but also, with a certain delay, the global supply chains, indicating the deepening of differences in the logistics sector. Industries that rely on global logistics supply chains are found to be highly susceptible to changes in transformation flexibility and changes in the configuration of supply chain networks. It has been established that the consequences of the unrest in Ukraine have exacerbated the financial, humanitarian, food, energy, social, and value of life crisis. In terms of impact on the Ukrainian logistics sector, they have led, among others, to the weakening/breaking of logistic links, the lack of potential to fully use them during wartime, and the intensification of security threats.
Conclusions: Among the logistics requirements, the safety and self-preservation function has become the most important. Therefore, an important task during wartime is to develop security mechanisms that ensure durability and efficiency, as well as operational and integrated supply chains with high adaptability to disruptions.

Keywords: COVID-2019, war, disruption, macroeconomic indicators, geopolitics, recession, supply chains, risk, security

INTRODUCTION

Given the dominance of radical uncertainties in certain regions of the world, along with local escalations of tensions, it is necessary to examine the parameters and influences on the security of global and local supply chains in highly competitive environments with various disruptions. Geopolitics is increasingly exerting pressure on all sectors of the economy. Consequently, the identification of dimensions of supply chain transformation during times of systemic disruptions is perceived as an important economic challenge due to the growing threats to the economic security of countries, especially their logistics sectors.

In Ukraine, there is a lack of economic instability, manifested through various

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disruptions: expectations of financial shocks related to high global debt levels (in 2021-2022), recession in economic sectors, the spread of the COVID-19 pandemic, climate change, food, energy, and humanitarian crises, as well as the ongoing hybrid war in Ukraine since 2014 and the active phase of the war conducted by the Russian Federation since 2022. These disruptions have a significant, multidirectional impact on the functioning of supply chains, thus determining their effectiveness. Often, these disruptions have an irresistible (force majeure) nature and are caused by factors and forces over which logistics chain participants have the least leverage and which are beyond their understanding and competencies. The unpredictability of the scale of negative consequences of such disruptions, and therefore the complexity of predicting scenarios for the development of events under conditions of instability, as well as the short periods for restoring logistics chains due to the action of local and territorially undefined centers of disruption in time and space, significantly complicate the mechanisms for making appropriate adaptive management decisions. Overcoming the uncertainty of the impact on the established mechanism of supply chain functioning is accompanied by a lack of both the participants' own experience in supply chains and an insufficient amount of theoretical and applied developments in the identification of mechanisms for adapting supply chains to the conditions of risk deployment caused by the researched disruptions. The outlined reveals the depth and relevance of solving the problem of identifying environmental factors for the development of logistics chains to solve the tasks of their effective functioning and development under the conditions of the action of various disruptions on them.

The article aims to examine the impact of major disruptions that destabilize global supply chains and supply chains in Ukraine and how they affect them. The research presented in the article focuses on the response of supply chains to disruptions in their environment. In this context, the issue of ensuring the security of supply chains becomes extremely important, which in the current reality is gaining special importance and is becoming the overriding goal of logistics. It should be remembered that the scope of broadly understood security is multifaceted. There are many factors that affect the security of supply chains. This article is an attempt to answer the following questions:

RQ1 – what are the main indicators of macroeconomic and geopolitical disruptions in global logistics chains and how do they affect fluctuations in world GDP?

RQ2 – how do current participants in supply chains assess the impact of disruptions on modern supply chains?

RQ3 – which types of security risk are connected with the logistics sector under disruptions?

To uncover research issues, this article is structured in a logically structured research framework: 1) presentation of types of disruption and substantiation of macroeconomic and geopolitical indicators of disruptions that affect the functioning of logistics supply chains; 2) survey research on the impact of disruptions on supply chain activities in Ukraine; 3) identification of the security risk associated with the logistics sector in a war environment.

RESEARCH METHODS

The subject of the study is the analysis of the main disruptions that destabilize supply chains. The research methodology of this article has been oriented towards a theoretical-utilitarian character of the conducted research and consists of the following stages (Fig. 1):

1. the bibliometric analysis conducted employing the systematic literature review method;
2. statistical analysis of the main macroeconomic indicators affecting the logistics sector in Ukraine and the global economy;
3. survey research conducted among respondents who are participants in supply chains;
4. conclusion – drawing conclusions in relation to the analyses made, e.g., including risks for the security of the supply chain environment.

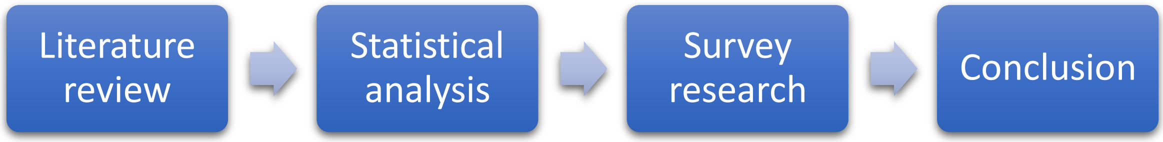

Fig. 1. Research methodology. Source: own elaboration.

The bibliometric analysis, conducted by employing the systematic literature review method, made it possible to present the current and fundamental aspects of the theory of economic activity of enterprises and the theory of crises. The impact of disruptions such as economic crises, financial instability, and risks related to the functioning of organizational units in the supply chain are discussed. The analysis underlines the need to study the economic and political environment during the disruption caused by the spread of COVID-19 and the active phase of the war in Ukraine with the RF, as well as their impact on logistics supply chains.

A statistical analysis was performed to analyze the dynamics of the main macroeconomic indicators of economic activity in Ukraine under the influence of various types of disturbances that are reflected in the logistics sector. Statistical data related to indicators such as GNP, Purchasing Managers' Index, Global Supply Chain Pressure Index, and Logistics Performance Index were analysed.

The structural element of the article was a survey. The study was aimed to analyze the opinions of the respondents about supply chain disruptions and their reactions to them. The empirical research of the authors in terms of conducting consumer survey research was directed at a group of the main market participants, specialized logistics operators of the "Transport, warehousing, postal, and courier activities sector and a group of stakeholders, and industry experts who have in-depth analytical information about the results of the researched sector, including specialists involved in scientific and educational activities in a given area.

The parameters of the survey research were:

– research method – survey of Ukrainian representatives of public organizations involved in logistics business, representatives of the scientific and educational sector, organizations using logistics services, and employees of enterprises representing the "Transport, warehousing, postal, and courier activities" sector according to the NACE[1];
– the questionnaire included 12 questions (of which the second question was divided into three blocks; the seventh question was divided into five blocks), regarding, among others, the most important factors affecting and hindering the operation of supply chains in individual sectors, response of supply chains to disruptions, ways to restore the stability of the supply chains
– types of questionnaire questions – open, closed, and closed with multiple choice answers (with the option of alternative answers), meaningful, and supporting questions;
– data collection tool – a Google Form questionnaire;
– according to the method of communication between the respondent and the researcher, the online mode was used in the survey process (given that the survey was conducted during the period of active hostilities in the country, which coincided with the period of restoration of functioning in the postwar period).

[1] NACE (The Statistical Classification of Economic Activities in the European Community) - is the industry standard classification system used in the European Union.

They used e-mail (60%), Facebook (30%), and LinkedIn (10%);
- by type of respondent – survey of top managers and midlevel managers, industry experts, and representatives of the scientific and educational sector (170 respondents);
- period of research – August–September 2022.

In the last stage of research work, based on the analyses carried out, as well as a survey, a discussion part was conducted, and conclusions were drawn on macro turbulence and geopolitical uncertainties to restore economic activity in logistics chains in Ukraine. Particular attention was also paid to the risk associated with the security of the logistics sector in the event of a disruption.

INDICATORS OF MACROECONOMIC AND GEOPOLITICAL DISRUPTIONS REFLECTED IN LOGISTICS SUPPLY CHAINS

During the development of economic systems under the influence of a large number of disruption factors, a 'crisis era' or a 'crisis society' is stated [Horbulin and Kachynskyi, 2010]. Therefore, it is fundamentally important to identify the causes and dynamics of crises in socioeconomic systems and to develop tools for effective management during disruptions in the context of security processes. For example, in Orel's work [Orel, 2019], the interrelation between system development and its security in the political plane is studied. The author stated that the depressed development of the political system leads to political destabilization and sociopolitical tension, and ensuring security in the political sphere is a prerequisite for the successful development of the examined system. As Orel notes, in the process of providing security, it is fundamental to clarify the essence of the factors that cause disruptions and dangers arising in economic systems.

Economic systems, according to the phases of their development, can be in unstable states in periods of economic decline outside the growth phase. It is known that in production and business cycles, the output curve describes a long upward trend with some upward and downward deviations with subsequent recovery to its crisis trend after a recession. Cerra and Saxena [2017] argue that recessions caused by different disruptions lead to irreversible output losses and 'landslides' in the output curve and differ depending on the frequency and depth of these disruptions. However, despite the factors that caused the disruptions, such as external political information influences (information aggression and asymmetry) or internal miscalculations in macroeconomic policy, as argued by Cerra and Saxena [2018], they are reflected in prolonging the duration of the recovery period and contribute to political polarization after systemic financial crises, which was also confirmed by Funke et al. [2016]. The high cost of financial crises and recessions calls for sound macroeconomic approaches and fiscal policies that shape the development environment of economic systems, that is:

a) financial regulation and compliance with prudential regulation to obtain an adequate level of leverage, studied by Blanchard et al. [2010], Caruana [2014], and Turner [2017];
b) promoting price stability, the main objective of monetary policy is dominant for central banks with a clear framework for inflation targeting to avoid financial bubbles and crises. This vector of research has interested Blanchard et al. [2010], who analyze how the Federal Reserve reacted to the 1987 stock market crash, the collapse of long-term capital management (LTCM), and the bursting of the technology bubble. In particular, Svensson argues [2016] that keeping interest rates above the required level to stabilize prices may increase the cost of the crisis due to a weakened economy and rising unemployment. For example, in Ukraine, the Roadmap of the National Bank of Ukraine (NBU) for the transition to inflation targeting (2016) has been established;
c) regulation of the amount of the accumulation of monetary reserves, which should become a buffer in case of a balance of payments crisis.

Supply chain risk management in an active and competitive environment deserves special attention. According to [Wu and Blackhurts, 2009; Samvedi et al., 2012], in a fuzzy business logistics environment, the absolute goal of structuring an efficient and effective supply chain makes it even more susceptible to risk. This can lead to a decline in product quality, loss of company image and reputation, supply disruptions [Cousins et al., 2004], stakeholder problems [Craighead et al., 2007], and a drop in company stock prices [Hendricks and Singhal, 2005]. Selected research works are related to supplier development [Nepal and Yadav, 2015; Hashim et al., 2017], identification of the supply chain input risk system [Garvey et al., 2015], and management of supply chain project risk [Mhatre et al., 2017; Sharma et al., 2017; Christopher and Peck, 2004] for many companies [Lücker and Seifert, 2017].

It should be noted that there is a significant legacy in the field of crisis theory and the development of applied tools to investigate the impact factors on the resilience of supply chains in the precrisis period. However, there is an acute need to study the economic and political environment during the disruptions caused by the spread of the pandemic and the active war phase in Ukraine with RF. There is also a need to study its impact on logistics supply chains, which have so far been little investigated and hence are relevant given the narrow horizon of the disruptions.

The sustainability process identified by the functioning of individual companies and supply chains during disruptions necessarily involves some transformation of resilient relationships within the object of study under the influence of the risk-formation environment triggered by these disruptions. Changes in the ways and methods of management in logistics chains under the influence of disruptions should be considered from the perspective of value creation at individual chain links. Such changes should also take into account the neutralization of the threat of these disruptions, aimed at increasing the profitability of the business in the long term for the partners involved in the chain or profit and reducing the costs of production in the short term. Examples of such disruptions include the 2008-2009 global financial crisis, Brexit, the spread of the COVID-19 pandemic, the RF's war in Ukraine (warfare since 2022 and hybrid information aggression since 2014 up to the present), which have transformed trade and investment linkages.

It is well known that the indicators of change that are inherent in the trend analysis of countries are levels of inflation, employment, investment expansion, the development of foreign exchange and capital markets, indicators of productive activity and enterprise competitiveness, etc. Among price increases and supply chain disruption, financial complications, declining trade, and investment flows, ensuring stability of production for domestic needs remains the dominant factor for which developed countries pay attention to ensure economic stability, while developing countries seek access to external commodity markets through active export activities.

Given the reflection of disruptions on the performance and security of global logistics chains, the authors believe that the main indicators of macroeconomic and geopolitical disruptions are:

- World GDP (Table 1) and Purchasing Managers' Index (PMI), which interpret the growth rate of global industrial and services production;
- Baltic Dry Index (BDI), which tracks prices in the dry cargo shipping sector;
- Capesize Index (CI), which tracks iron ore and coal cargoes of 150,000 tons;
- Panamax Index, which tracks shipments of 60,000 to 70,000 tons of coal or grain;
- The Baltic Supramax Index (BSI) is a price index for dry bulk cargo used in shipping. It is part of the Baltic Dry Index;
- Global Supply Chain Pressure Index (GSCPI) is a reflection of disruptions in the logistics supply chain. Positive values of this index indicate by how many standard deviations the index is above the average value, i.e., more supply chain disruptions are observed at higher Index points;
- Logistics Performance Index (LPI) as a factor of influence on trade in a

comparative analysis of countries. LPI consists of six components: efficiency of the customs clearance process (speed, simplicity, and predictability of formalities), quality of trade and transport infrastructure (ports, railways, and information support), ease of international transport clearance at competitive prices, quality of logistics services, cargo tracking criterion, and time criterion (timeliness). It should be interpreted as an identification tool to identify potential challenges and opportunities in trade logistics.

Table 1. Analysis of World GDP dynamics and Ukraine's GDP

Year	World GDP, trillion USD	Deviations from the previous period	Real GDP (year-earlier prices), million UAH	Deviations from the previous period
2008	63.71	-	-	-
2009	60.44	0.9487	-	-
2010	66.16	1.0946	-	-
2011	73.48	1.1106	-	-
2012	75.17	1.0230	1304064	-
2013	77.33	1.0287	1410609	1.0817
2014	79.47	1.0277	1365123	0.9678
2015	75.23	0.9466	1430290	1.0477
2016	76.42	1.0158	2034430	1.4224
2017	81.33	1.0643	2445587	1.2021
2018	86.34	1.0616	3083409	1.2608
2019	87.61	1.0147	3675728	1.1921
2020	84.71	0.9669	3818456	1.0388
2021	93.86	1.1080	4363582	1.1428
2022 (forecast)	95.00	1.0121	2395607	0.5490

Source: own elaboration based on [GDP in Ukraine, 2022; The World Bank Data, 2023]

Analysis of World GDP over the period 2008–2022 indicated its dynamic response to disruptions caused, for example, by the global financial crisis of 2008–2009, during the active period of which World GDP declined from 63.71 trillion USD to 60.44 trillion USD, a decrease of 5.13% compared to the previous period. Global GDP responded to the European migration crisis in 2015 by falling from 79.47 to 75.23 trillion USD, a decrease of 5.34%, compared to the previous year. In 2020, during the period of an active pandemic, the global GDP was 84.71 trillion USD, a decrease of 3.31% compared to 2019.

The Global Supply Chain Pressure Index (GSCPI) can be considered as one of the disruption indicators in global supply chains. The GSCPI summarizes 27 variables, including cross-border transport costs, production volumes in China, the EU, the UK, Japan, South Korea, Taiwan, and the USA, national purchasing managers' indices, global freight rates (including the container index), and airfreight price indices. The higher the positive GSCPI values, the more significant the supply chain disruption; negative values of this index indicate a standard deviation of the index below the average. The dynamics of PMI and GSCPI are shown in Figure 2 and Table 2.

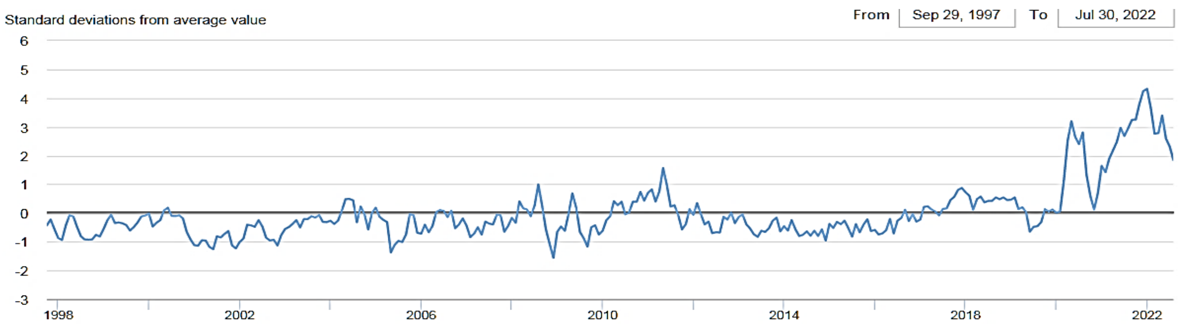

Fig. 2. Global Supply Chain Pressure Index: long-term trend. Source: [Cerra and Saxena, 2018].

The disruptions analyzed were not only reflected by fluctuations in global GDP but also, with a certain delay, in global supply chains. This was interpreted by GSCPI fluctuations, with the greatest deviation during the pandemic when the pressure peak reached a value of more than 4 points (October-December 2021).

Table 2. Analysis of trends in the GSCPI during a period of active disruptions (monthly)

Year	Month												12/1 (2021) 7/1 (2022)
	1	2	3	4	5	6	7	8	9	10	11	12	
2021	1.42	1.89	2.18	2.47	2.68	2.95	3.24	3.25	3.80	4.24	4.32	4.24	2.99
2022	3.65	2.76	2.78	3.39	2.59	2.31	1.84	-	-	-	-	-	0.50
2022/2021	2.57	1.46	1.28	1.37	0.97	0.78	0.57	-	-	-	-	-	- 2.00 r. c.

Source: own elaboration based on [Cerra and Saxena, 2018].

As shown in Table 2, the largest disruptions in supply chains for the period January 2021-July 2022 were observed with an increasing trend in October-December 2021 and with a further downward trend (with slight increasing fluctuations in March-April) until July 2022, where the GSCPI was 1.84 points. GSCPI is an integral part of PMI, and the relationship between them is shown in Figure 3.

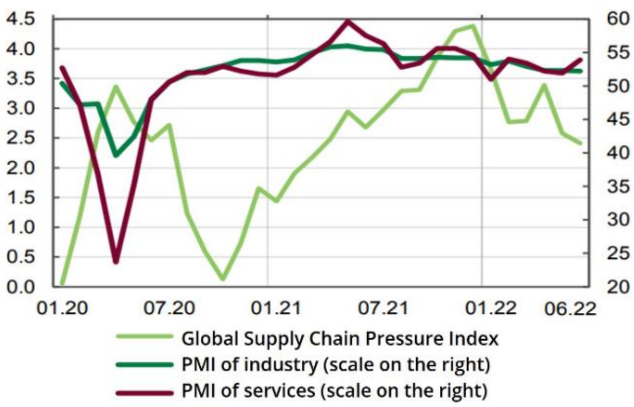

Fig. 3. Global PMI and GSCPI: an overview of trends. Source: [Global Supply Chain Pressure Index, 2022].

According to Figure 2, the global PMI indicates a deepening divergence caused by the spread of the pandemic and the war in Ukraine. For example, analysis of the effects of overcoming the COVID-19 pandemic indicated that industries relying on global logistics supply chains have a high vulnerability in terms of transformation elasticity and changes in supply chain configuration. This increased the relevance of reviewing the organizational principles of the global economic system and strengthening the role of local manufacturing, at least during the period necessary for the recovery of the economy, which is typical of a V-shaped recovery due to a recession with a short recovery in time.

Almost simultaneously, the period of economic recovery from the consequences of the pandemic coincided with downward trends due to the artificial (hybrid nature) escalation of energy price crises in Europe (autumn 2021). Due to the consequences of the financial assistance policy, a "price shock" with a certain time lag (March 2022) was reflected in the industry and service sectors, among other things, due to the increasing global oil and gas prices (Figure 4).

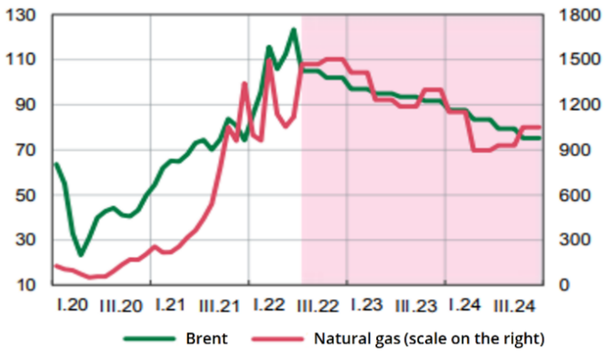

Fig. 4. World Brent crude oil prices (UAH/barrel), natural gas prices on the Dutch market (TTF UAH/kcm): an overview of the dynamics during the period of active disruptions. Source: [Minfin, 2022].

Narrow indicators which can indicate the development of online freight volumes are:

- Baltic Dry Index, which for example on 16 August 2022 for the fourth consecutive session, has shown a loss, falling by 1.2% to 1.387 points, the lowest level in more than six months in 2022;
- The Capesize Index declined for the fourth consecutive session on the same day, falling by 3.6% to 1,059 points—the lowest level since 27 January 2022;
- The Panamax Index declined for 16 consecutive sessions, dropping 35 points to 1.850 points and reaching the biggest drop in August 2022;
- Meanwhile, the Supramax Index rose for a third straight session, rising 19 points to 1,626 points—its best result of this index in nearly three months.

In Ukraine, according to the authors, indicators of macroeconomic and geopolitical disruptions, which are reflected with a certain time lag in the supply chain, should be indicators such as:

- real GDP, which takes into account the transformation of output while adjusting for changes in price levels (Table 3);
- the unemployment rate, which against the background of the war in Ukraine has a more pronounced conjunctural nature and reflects the reaction of internally displaced persons and forced emigration from Ukraine (Table 3);
- Consumer Sentiment Index (CSI), which is a projected indicator of the possible change in consumer demand in the future (Table 4);
- Business Activity Expectation Index (BAEI), which interprets the prospects of economic activity in various sectors of the economy at an equilibrium value of 50.0 (Table 4);
- Consumer Price Index (CPI) (inflation index) (Table 4);
- Basic Industry Production Index (BIPI) (Table 4).

With the ongoing war on the part of the RF, trade relations have become more difficult, mainly due to a decline in Ukrainian food exports. High import dependency and sanctions have accelerated food inflation in most countries. As a result, raising prices in world markets and creating grounds for hunger in more than 100 countries. All this has put pressure on logistics chains around the world and in Ukraine.

As shown in Table 3, real GDP in 2022 is projected to be 54.9% of the figure in 2021. The unemployment rate is projected to rise by 2.81% in 2022 relative to 2021. These figures indicated a negative trend relative to previous periods, which are related to country, war, migration, higher energy prices, and dealing with the effects of the pandemic. In 2021/2020, real GDP growth was 114.28% with a 104.04% increase in the unemployment rate. In 2020, real GDP rose by 3.88%, with a growth of 115.12% growth in the unemployment rate, compared to 2019. These periods were marked by the dominant impact of pandemic growth on economic activity in Ukraine. Other indicators to assess economic activity in Ukraine are summarised in Table 4.

Table 3. Main baseline indicators of economic activity identification in Ukraine during the period of active disruptions (by quarter)

Period	Real GDP, UAH mln	Deviations from the corresponding period of the previous year	The unemployment rate, %	Deviations from the corresponding period of the previous year
2018	-	-	-	-
1st quarter	766150	-	9.6	-
2nd quarter	875733	-	8.8	-
3rd quarter	1050095	-	8.4	-
4th quarter	983750	-	8.6	-
2019	**3675728**	-	**8.6**	-
1st quarter	821210	1.0719	8.9	0.9271
2nd quarter	842935	0.9625	9.6	1.0909
3rd quarter	1095567	1.0433	9.7	1.1546
4th quarter	1058744	1.0762	9.9	1.1512
2020	**3818456**	**1.0388**	**9.9**	**1.1512**
1st quarter	887884	1.0812	10.9	1.2247
2nd quarter	987871	1.1719	10.3	1.0729
3rd quarter	1243962	1.1355	10	1.0309
4th quarter	1243865	1.1749	10.3	1.0404
2021	**4363582**	**1.1428**	**10.3**	**1.0404**
1st quarter	753814	0.8490	27	2.4771
2nd quarter (forecast)	592723	0.600	35	3.3981
3rd quarter (forecast)	777476	0.6250	-	-
4th quarter (forecast)	777416	0.6250	-	-
2022 (forecast)	2395607	0.5490	28.9	2.8059

Source: own elaboration based on [State Statistics Service of Ukraine, 2022].

Table 4. Selected measures of economic activity in Ukraine during the period of active disruptions (by month)

Indicator	CSI, items	BAEI	CPI, %	CPI, cumulative, %	BIPI, %
		2021			
January	60.7	37.6	101.3	101.3	-3.5
February	69.1	48.8	101.0	102.3	-3.9
March	67.8	51.4	101.7	104.1	0.3
April	77.2	46.9	100.7	104.8	19.0
May	71.3	50.5	101.3	106.1	5.0
June	72.9	51.6	100.2	106.4	2.5
July	71.3	50.8	100.1	106.5	2.7
August	73.7	53.4	99.8	106.3	7.0
September	69.7	53.1	101.2	107.5	-3.8
October	68.8	51.4	100.9	108.5	20.6
November	66.0	48.9	100.8	109.4	14.4
December	67.2	48.6	100.6	110.0	-0.7
December/January (2021)	1.11	1.29	0.99	1.09	0.2
		2022			
January	62.3	40.5	101.3	101.3	7.5
February	64.1	-	101.6	102.9	-
March	92.4	-	104.5	107.6	-
April	85.6	-	100.3	110.9	-
May	84.5	-	102.7	113.9	-
June	78.1	41.3	103.1	117.4	-
July	73.2	43.6	100.7	118.2	-
August	75.6	44.1	101.1	119.5	-
September	86.0	46.1	101.9	121.8	-
October	83.6	44.9	102.5	124.8	-
November	85.2	42.7	100.7	125.7	-
December	83.9	42.1	100.7	126.6	-
December/January (2022)		1.0395			
		2023			
January	83.8	37.5	100.8	100.8	-

Source: own elaboration based on [State Statistics Service of Ukraine, 2022; National Bank of Ukraine, 2022; The World Bank, 2022].

The Consumer Sentiment Index (CSI) as an indicator reflecting the growth potential of consumer demand, and therefore the growth of demand in the logistics sector, shows the highest value in April 2021 – 77.2 p. and in March 2022 – 92.4 p. However, all rates are below 100 p., which means the prevailing negative trends in the assessment of consumer sentiment in society in the period under consideration.

The Business Activity Expectation Index (BAEI) in Ukraine in 2021 did not reach its equilibrium value in January-February, April, and November-December due to the spread of the pandemic and shows a negative assessment of the prospects for economic activity. From January to July in 2022, BAEI values were below the equilibrium value due to the war in Ukraine, the destruction of production and logistics capacities, the forced transformation of supply chains, blocked seaports, rising energy prices, increased production costs for companies, and worsening inflation expectations.

The cumulative Consumer Price Index (CPI) stood at 110% in 2021, compared to 117.4% in January-June 2022.

In January, February, and September 2021, the Basic Industry Production Index (BIPI) was negative: -3.5%; -3.9%, and -3.8%, respectively. However, it is not estimated for the year 2022 from February to the present due to the war.

The dynamics of the Logistics Performance Index (LPI) for 2007-2018, which comprehensively reflects changes in the logistics sector in Ukraine according to six factors, was analyzed (Table 5).

Table 5. Dynamics of the Logistics Performance Index: 2007–2018

Year	LPI rank	LPI Score	Customs	Infrastructure	International shipments	Logistics competence	Tracking & tracing	Timeliness
2007	73	2.55	2.22	2.35	2.83	2.41	2.53	3.31
2010	102	2.57	2.02	2.44	2.79	2.59	2.49	3.06
2012	66	2.85	2.41	2.69	2.72	2.85	3.15	3.31
2014	61	2.98	2.69	2.65	2.95	2.84	3.20	3.51
2016	80	2.74	2.30	2.49	2.59	2.55	2.96	3.51
2018	69	2.83	2.49	2.22	2.83	2.84	3.11	3.42

Source: own elaboration based on [The World Bank, 2022].

For example, in 2018, the on-time delivery subindex was 3.42—lower than its level in 2014 and 2016, which was 3.51. In addition, in this period, the trade and transport infrastructure subindex as a logistics priority parameter had the lowest value of 2.22. The analysis of the Logistics Performance Index indicated that the growing conjuncture of the Ukrainian logistics services market in the international transport segment requires urgent improvement of logistics infrastructure facilities and the development of an organization and economic mechanism in the context of automation of logistics processes.

RESEARCH ON THE IMPACT OF DISRUPTIONS ON THE FUNCTIONING OF THE SUPPLY CHAINS

Forced transformation processes caused by the Russian war in Ukraine have significantly changed the specifics of supply chain operations. The latter are now influenced by transformational processes in the global logistics environment, which is characterized by its uncertainty and magnitude of change. It is argued that the instability, uncertainty, complexity, and ambiguity caused by military action in Ukraine, as well as fierce global competition and the realization of challenges with low likelihood but with powerful forces of influence, only reinforce the trends that have emerged in global supply chains.

The logistics supply chain, the country's transportation system, the warehousing segment, and other actors involved in the logistics sector inevitably react to the emergence of crises and the need for economic actors to adapt to their consequences. Competition, economic development, and supply chain security are now integral tenets of the operating environment of all supply chain actors under disruptions. Recent disruptions have confirmed the restructuring of economies and the increasing uncertainty of market interactions under the influence of escalating geopolitical tensions, intensifying security challenges that have an exceptional impact. This has forced logistics chains to adapt, based on resilience and flexibility.

Creation and adaptation of the principles of organizational and technological cooperation of various modes of transport (based on modal interoperability and integration of existing modes of transport), coordination and synchronization of transport and logistics processes to overcome crisis phenomena, development of logistics mobility, creation of partnerships between participants in the cargo supply chain in qualitatively new market conditions, as well as a joint response of international institutions to the crisis, global solidarity, cross-border cooperation in creating new infrastructure facilities to increase mobility, etc. activate partnership in various dimensions and form a safe environment for the transport process to maintain individual territories and the entire country.

The purpose of the study is to present the results of the assessment of the adaptive reactions of supply chain participants to disruptions in the post-COVID-19 and war periods in Ukraine. To achieve the main goal, the following objectives must be met:

- identify the groups of the most important disruptions exerting active pressure on supply chains;
- identify the core of the multidimensional threats which accompany supply chains under disruption conditions;
- study the transformation of market conditions elements under the impact of disruptions, which require the adaptation of production and economic, including operational and logistics activities of supply chain actors;
- identify the most favourable logistics and other support measures to restore the economic efficiency of supply chains.

The target audience for the study was professionals involved in the logistics industry, industry experts, and representatives of scientific and educational activities. Responses were received from 220 respondents. The distribution of the respondents was as follows: specialised logistics operators (transport company, public warehouse, cargo terminal, customs broker, stevedore) – 57.1% of the respondents; the logistics division of a manufacturing/trading company that performs logistics operations independently – 14.3% of the respondents; integrated logistics 3PL operator – 7.1%; virtual logistics 5PL integrator – 2.4%; industry experts, including from the science and education sector– 19.1%. Respondents involved in foreign trade activities in supply chains were distributed as follows: carry out export and import operations – 26.2% of respondents; carry out export operations only – 9.5% of respondents; carry out import operations only – 4.8% of respondents; and do not carry out foreign economic transactions – 59.5% of respondents. The responses of the respondents on the issues discussed are presented below.

In the group of the most significant geopolitical and macroeconomic factors that affect the prospects of economic activity and the safety of logistics chains (1^{st} question of research), the majority of respondents (82.1%) attributed the continuation of intensive hostilities in the war with Russia and the blocking of cargo exports through Ukrainian ports (74.4%). The second group distinguished by the respondents included factors such as the spread of the pandemic (35.9%); fluctuation of the exchange rate of hryvnia to Euro/USD/currency restrictions (25.6%); worsening of inflation expectations/increase of credit rates/rise in energy prices (23.1%); migration/migration during the war (23.1%). Respondents indicated a group of geopolitical factors as priority impact factors, and the issue of overcoming the effects of the spread of the pandemic in the conditions of war, which is seasonal for the target audience, is not among the priority forces of action.

Among the most significant threats requiring operational intervention during disruptions (2^{nd}*a* question of research), 53.8% of the respondents indicated the threat of terrorism and crime, 30.8% of the respondents indicated the threat of politically motivated attacks, and 15.4% of the respondents indicated the threat of forced migration. Other responses included the factor of mobilizing workers to the front line. Among the latest hacker attacks (October 18, 2022) linked to the security environment was the spread of the Prestige computer virus to transport and logistics companies in Poland and Ukraine, which are part of commercial, humanitarian, and military supply chains. Similarly, FoxBlade (a trojan horse wiper malware) activity was detected on 23 February 2022 at the start of the full-scale invasion of Ukraine, which is linked to the RF.

The disruption of considerable force of the action, which follows one after another in Ukraine (as a pandemic or war), has emphasized the economic component and the social focus of business. Among the economic threats accompanying supply chain participants during disruptions (2nd*b* question of research), 46.2% of respondents pointed to a drop in purchasing power, 35.8% to an increase in operating costs, 10.3% to a decrease in transactions in the supply chain, and 7.7% to a decrease in income of supply chain actors.

Among social threats to supply chain operations during the disruptions (2nd*c* question of research), 59% of the surveyed noted the loss of professional staff, 33.3% noted forced pay cuts by employees, and 5.1% and 2.6% noted factors such as forced labor migration and feelings of insecurity, respectively.

Among the market factors that affected supply chain operations during disruptions (3rd question of research), respondents identified the following factors: disruption of logistics links/ changes in transport capacity (41% of respondents); business closures in active combat areas (20.5% of respondents); inability to store goods in damaged locations (15.4%); steep price increases for goods and logistics services (10.3%); structural changes/loss of orders (7.7%); and damage/destruction/theft of goods at retail sites or distribution centers in occupied territories (5.1%).

As a response to supply chain disruptions, respondents outlined the following (4th question of research): forced rerouting of goods (38.5% of surveyed), the opening of new distribution centers, including in secure areas (28.2% of surveyed), finding consumers in new territorial markets (20.5%), forced change of product suppliers (10.3%), and recourse to new 3-PL operators (2.5%).

Among the problems that most affect operational activities in the supply chain (5th question of research), the respondents listed the following: ensuring security across all segments of the supply chain (38.5% of the respondents); further increase in supply chain costs (23.1%), financial and other types of risk (20.5%) customer centricity (7.7%); and lost productivity and flexibility (each 5.1%).

In the case of increased interaction with counterparties due to disruptions (6th question of research), respondents focused on interaction issues: in the B2B segment – 41.0% of respondents; in the E2E segment interaction (online interaction) – 28.2%; direct to the customer (D2C) – 20.5%; and between business and government (B2G) – 10.3% of respondents.

Among the factors that hinder logistics chains in the road transport sector during a period of disruptions (7th*a* question of research), respondents highlighted the following: a sharp increase in fuel and lubricant prices - 35.9% of the surveyed; shortage and fuel problems – 17.9% of the surveyed; problems with the formation of the lot of packages in the reverse direction – 15.4%; renegotiation of long-term contracts due to increasing costs – 12.8%; lack of established routes – 7.7%; an increase of freight rates by carriers and price pressure on Ukrainian producers – 5.2%; additional costs related to the need to obtain visas and limited capacity of customs offices – each factor 2.6% respectively.

To the question ‘What factors complicate the work of logistics chains in the period of disruptions in the railway transport sector?’ (7th*b* question of research) the answers of the respondents were distributed as follows: the closed market for private operators and the low involvement of intermodal operators in the sector business models – 41% of the respondents; different track width in Ukraine and Europe – 30.8%; significant tariff preferences for certain consumer groups – 17.9%; state regulation of tariff policy in the sector – 10.3% of the respondents.

To the question 'What factors complicate the work of logistics chains in the period of disruptions in the water transport sector?’ (7th*c* question of research) the answers were distributed as follows: blocking of Ukrainian ports – 66.6% of the surveyed; shortage of port capacities with a mismatch of transshipment capacities, shortage of ships, leading to increased queues in ports/duration of cargo handling in ports/increased delivery time – 17.9% of the surveyed; further growth of freight rates (because of pandemic/war/vessel fuel excise) – 7.7%; non-compliance with the schedule of sea voyages – 2.6%; forced competition for empty containers with Turkey as a regional center of gravity for transport companies – 2.6%; shortage of ships leading to increased queues at ports/duration of cargo handling at ports/cargo delivery time – 2.6% of respondents.

In the period of disruptions, the development of export supply chains in shipping regions with the involvement of water transport is determined by exceptional institutional support and a competitive advantage between industries concerning rail transportation over long and especially short distances, regardless of the ports blocked by RF and the destruction of part of the water infrastructures and suprastructure facilities in the occupied territories. In the case of placing a significant share of industrial enterprises, processing/transshipment, and other capacities in remote areas from ports, factors that stimulate the development of short-distance road transport (which is determined in conditions of disruptions by greater mobility, flexibility, and safety of transportation) are the high cost of rail transportation on short distances, as well as the high cost of freight due to the presence of excise duty in marine fuel.

According to respondents, factors complicating supply chain operations during a period of disruptions in the warehousing sector (7th*d* question of research) were a shortage of warehouses with special storage conditions (pharmaceuticals, dangerous goods, etc.) – 38.5% of the surveyed; decreasing vacancy rates for large warehouse properties (class A, A+) in safe regions – 35.9% of the surveyed; and unfilled orders – 23.1%. Other responses included destroying 50% of storage space for cold logistics, theft of vehicles in damaged locations, raising rental rates for commercial cargo in secure areas and higher rental rates in Ukrainian warehouses compared to European countries – 2.6% of respondents. The analysis of secondary information indicates the active use of warehouses during the war for humanitarian and military needs, with preferences for cargo owners (temporary exemptions, deferrals, and discounts) and taking into account the social responsibility of the business; relocation of logistical hubs to a safer western region and dispersal of stocks there to diversify security risks; and development of demand-side industries for warehousing services, e.g., processing industry (including food processing, agribusiness, metallurgy, etc.) and online and retail sectors.

Generalizing factors of resistance to supply chain operations during the disruption period (7th*e* question of research) were as follows: increased logistics risks related to customs clearance procedures, transport, and product distribution (59.5% of respondents); high sensitivity to natural disasters and other force majeure events (23.8% of respondents); intentional cybercrime (phishing attacks, website hacking, malicious software corruption, ransomware attacks, insecure web services, etc.) (7.1%); the process of providing jobs and housing to some displaced staff (7.1%); and a shortage of containers (2.5%).

In the opinion of the surveyed, transformations in supply patterns, according to the manifestations of disruptions, have taken place as follows (8th question of research): activation of Internet sales (35.7% of respondents); the activation of hybrid delivery models without the accumulation of product residuals (21.4% of respondents); an increase in the number of supply chains and the provision of a narrow range of products through small cross-docking warehouses (19%); a shift from centralized supply and towards a delivery model involving regional warehouses (9.5%); expanding the pool of local suppliers and moving towards multiple sources of supply (7.1%); the regional warehousing model remained unchanged (4.8%); and the centralized supply model remained unchanged (2.4%).

To restore the stability of the supply chains during the period of disruptions, the respondents are focusing on (9th question of research) improving the structural efficiency of the supply chain, including through the formation of optimal logistics systems, precise business processes, and dynamic organizational change (35.7% of respondents); creating a competitive cost/multichannel/flexibility/technology/human resource advantage (23.8%); combining customs, fiscal, and logistics support for international business with tactical know-how (11.9%); establishment of a risk management system to restore transparency and end-to-end management (9.5%); automation and digitalization of business processes (9.5%); applying sustainable growth principles to the logistics ecosystem (4.8%); and compliance with corporate social responsibility (4.8%).

According to the respondents, measures to liberalise the terms of trade and other preferences that would contribute to the recovery of economic activity of logistics chains would be (10th question of research) the abolition of import duties and quotas on Ukrainian exports for one year (2022) – 42.9% of the respondents; elimination of requirements to return budgetary funds by farmers in case of loss of assets during the war – 2.4% of the surveyed; state railway transport insurance if insurance companies refuse to provide it (from April 1, 2022) – 7.1%; and simplification of rules for declaration and control of transit movement of goods to the European region (EU, EFTA, Turkey, Macedonia and Serbia) using NCTS – 47.6%.

Among the most important institutional expectations during the disruptions (11th question of research), respondents indicated the following: the acquisition of full EU membership (45.2% of surveyed); establishment of an infrastructure rehabilitation program under the auspices of the G7 (23.8%); expansion of external financing of Ukrainian business by international financial institutions (European Bank for Reconstruction and Development, European Investment Bank, International Finance Corporation of the World Bank Group, German State Development Bank KfW) (21.4%); SME participation in the 'Affordable loans 5-7-9%' program and war risk insurance (7.1%); and establishment of a trust fund under the auspices of the World Bank for infrastructure rehabilitation projects (using the 'Register of Damaged and Destroyed Property' platform) (2.4%).

The drivers to restore resilience of supply chains during disruptions (12th question of research) in the opinions of the surveyed are improved security across all business segments (28.5% of respondents); supply chain automation (16.7% of respondents); growth in e-commerce (14.3%); increased demand for express deliveries (14.3%); efficient cost management (11.9%); and supply chain integration (7.1%). Retail trade development, expansion of broadband Internet coverage, and the development of cloud solutions each accounted for 2.4% of respondents' answers.

DISCUSSION

According to the results of the research, logistics supply chains respond significantly to a variety of economic (including financial) geopolitical, social, and other types of disruption, according to the specific nature of a particular disruption with a given time lag. Among the most significant disruptions affecting supply chain security are the impact of the pandemic and the war in Ukraine. While the pandemic changes consumption patterns towards meeting basic needs, where chains involved in foreign economic activities face the threat of border closures and longer delivery times, war entails an economic recession with associated inflation, higher energy costs, and threats to the security of people, cargo, and supra- and infrastructure facilities.

Current literature on supply chain disruptions caused by the Russo-Ukrainian War focus either on selected industrial sectors, such as food [Jagtap et al., 2022] or energy [Cui et al., 2023], on Western European enterprises such as Germany [Aksoy et al., 2023] or Italy [Ropele and Tagliabracci, 2023], or focus on global economics [Guénette et al., 2022; Paché, 2022; Nguyen et al., 2022]. This study focuses mainly on supply chains in Ukraine and complements and extends the knowledge of disruptions affecting the functioning of participating enterprises.

The following generalizations have been made regarding measures to liberalise trade conditions and other preferences that will contribute to the restoration of economic activity in logistics chains. Supply chains involved in external economic activities face high tariff and nontariff barriers in times of disruptions, exceeding the limitations for external exporters in the domestic market. Consequently, the level of tariff protection for chains entering the Ukrainian market is often higher than for domestic export-oriented logistics chains, creating a significant level of asymmetry for domestic supply chains relative to external supply chains. Examples include the excess of average import duty rates of foreign countries compared to Ukraine, disparities in import rates for food and non-food products, the practice of applying tariff quotas on certain goods, the exclusion of certain goods from the free import regime, and the availability of products subject to mandatory laboratory inspection.

The establishment of a free trade zone has a positive direct impact on supply chains, in terms of the application of nontariff barriers to trade and the liberalization of import duties on mutual trade between partners while maintaining a surplus in trade in goods and strong export growth over import growth for domestic supply chains. Among the constituent indirect effects, the growth of real GDP, welfare, and other macroeconomic indicators are worth mentioning. Income growth is expected to be strongest for unskilled labor and capital, given some rebalancing of the economy.

At the core of multi-vector threats that accompany logistics chains in conditions of disruptions, in addition to traditional operational threats, threats related to the security component at all stages of the value-added creation are becoming more relevant in the supply chain. The security environment of the supply chain operation proved that external disruptions have a specific impact on the activity of supply chains and contribute to the formation of force majeure risks, to which logistics chains can only adapt their activities. The effect of force majeure risks, amplified by the exacerbation of logistics risks in war, in particular those related to customs clearance procedures, transportation, storage, and distribution in the context of the need to assess the supply chain environment, requires the study of the specific impact of the combination of risks on individual segments of the logistics sector. This allows the formation of attributes of supply chain environment security risks such as:

– risks of loss/damage/restriction of access to infrastructure and suprastructure facilities;
– risks of loss/damage/theft of cargo;
– organizational and economic risks, structured into risks of forced structural changes in the supply chain (changes in counterparties in the network, terms of cooperation between them), and related risks of reduced economic efficiency and performance of the supply chain, affecting long-term business profitability;
– health and safety risks to employees, external counterparties, and other stakeholders.

CONCLUSION

The analysis of supply chain responsiveness to disruption showed that the sensitivity of supply chains to disruptions of a significant magnitude is direct, with a relatively high degree of responsiveness of supply chain mechanisms to disruptions and refers to short-term responsiveness and long-term recovery of economic efficiency at all stages of value addition. As noted in the study, with increasing macro turbulence and geopolitical uncertainties, there has been a cost-of-living crisis reflected in consumers' purchasing power and purchasing power levels and in the context of supply chains, security component issues and supply chain security concerns. Institutional support for the logistics business, in particular trade liberalization and other preferences, has a significant role to play given the urgent need to restore the economic activity of logistics chains in Ukraine.

The productivity and flexibility of operational activities in logistics chains under conditions of disruptions (under the influence of the artificial shortage of energy carriers formed in Europe, the convergence of the economies of Russia and China, and sanctions restrictions concerning the destruction of Russian logistics chains) is aimed at meeting the needs of the client and is being restructured in the direction of strengthening the trend of localization and transfer of chains deliveries to the country of production or sale of own product. Against the backdrop of disruptions, companies are forced to rebuild their supply chain networks. The latter can resort to changing the size and number of points in retail networks, transforming the number of stocks or locations of warehouse facilities towards safe regions, deepening cooperation in the field of supplies, etc. In the case of global sourcing, the impact of the pandemic forced companies to resort to finding alternative sources of supply along with China (the leader in supply) resorting to a combination of global, regional, or local elements in the supply network.

The aspects discussed in this article are up-to-date, important, and require further research, namely: investigating the factors that contribute to the direct sensitivity of supply chains to disruptions of significant magnitude, and exploring the mechanisms that enhance the short-term responsiveness and long-term recovery of economic efficiency at different stages of value addition; examining the impact of increasing macro turbulence and geopolitical uncertainties on supply chain security and identifying strategies to mitigate these challenges to ensure smooth logistics operations; and exploring how companies are restructuring their networks and deepening supply cooperation to ensure operational continuity and resilience.

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ORIGINAL PAPER

ACCEPTANCE OF E-VEHICLES FOR LAST-MILE PARCEL DELIVERY FROM THE PERSPECTIVE OF DRIVERS: A STUDY IN TURKIYE

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ABSTRACT. Background: Last-mile delivery constitutes the most inefficient and costly part of logistics processes, thus increasing the importance of research in this area. Numerous alternative solutions and current technological advancements are being investigated to reduce the negative effects and make it more efficient and cost-effective. One of these alternatives is the use of electric vehicles for last-mile delivery. There is limited research on factors influencing user acceptance in the literature, and also a lack of studies on factors influencing driver acceptance. In this study, the authors aim to investigate the factors influencing drivers' acceptance of using electric vehicles for LMD of small and medium-sized parcels.

Methods: This study examines the factors influencing drivers' acceptance of e-vehicles for last-mile delivery within the framework of the Technology Acceptance Model (TAM). In addition to the basic TAM variables, the current research adds the independent variables of environmental concern and enjoyment to the conceptual model.

Results: Based on data from 180 participants in Turkiye, it was observed that environmental concern and perceived ease of use did not have an impact on perceived usefulness. Furthermore, the lack of influence of enjoyment on intentions is another important finding of the research. However, the other hypotheses were supported.

Conclusions: Based on the present research It is understood that drivers need time to fully adopt electric vehicles. The increasing integration and automation efforts among relevant parties, as well as the adaptation of vehicles for large-scale shipments, will contribute to the increased use of electric vehicles. Besides, technical issues related to electric vehicle delivery, as well as traffic regulations, should be promptly planned, and real-life tests and pilot programs should be accelerated and expanded.

Keywords: Last-mile Delivery, E-vehicles, TAM, Structural Equation Model

INTRODUCTION

Logistics processes are generally defined in three stages: first-mile logistics, middle-mile logistics, and last-mile logistics. The last stage involves multiple distribution points and accounts for more than half of transportation costs. In this regard, the use of new technologies and business models plays a facilitating role in problem-solving [Kåresdotter et al. 2022]. In recent years, last-mile logistics (LMD), which constitutes the final stage of business-to-consumer (B2C) online sales, has gained increasing significance in terms of efficient logistics management [Lim et al. 2018, Liu et al. 2019]. Due to factors such as challenging service levels, the multitude and dispersal of delivery points, LMD is considered the most inefficient and costly process for companies, and encompasses all logistics activities related to the delivery of shipments to private customer households in urban areas [Asdecker 2021, Jacobs et al. 2019, Macioszek, 2018, Moshref-Javadi et al. 2020]. According to [Boysen et al. 2021], LMD starts at an origin point (depot), where the goods to be delivered to the respective urban area arrive after long-haul transportation, and it involves the final delivery of the goods to the customer after one or more transportation and storage process steps. Last-mile deliveries are categorized based on the type of goods transported, such as grocery shopping, ready-

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made meals, courier services, large appliances, and packages [Allen et al. 2018].

Door-to-door services pose challenges for both companies and cities in various aspects. The most significant challenges include the increasing number of packages, deliveries, and vehicles due to online sales, costs, consumers' expectations for personalized and flexible services, companies' commitments to fast delivery, higher supplier costs, stricter environmental regulations, increased parking space requirements, vehicle breakdowns, greenhouse gas emissions, security risks, fuel consumption, noise, and traffic congestion [Assmann et al. 2019, Hu et al. 2019, Park et al. 2016].

When examining the academic literature, it can be observed that LMD is generally studied in three contexts: environmental sustainability, effectiveness (service level), and efficiency (costs) [Mangiaracina et al. 2019]. Both academia and the business world agree that LMD is one of the most critical logistics processes [Lim et al. 2018]. Research conducted in this context indicate that new technologies, transportation vehicles, and innovative strategies enable more effective, efficient and cost-effective LMD, particularly in urban areas [Balaska et al. 2022, Kulkarni and Barge 2020, Savelsbergh and Van Woensel 2016]. One of these innovations is the use of electric vehicles for LMD. However, such use is still in its infancy. Undoubtedly, consumer acceptance is a critical factor in the success of a technology, alongside technological maturity. In this context, identifying and understanding the factors that influence consumer acceptance is of great importance [Punakivi and Tanskanen 2002, Asdecker 2021, Osakwe et al. 2022]. Literature research indicates that the number of studies on the use of the relevant technology in last-mile parcel delivery is very limited. Furthermore, no study specifically focusing on Turkiye has been found. Additionally, no research has been encountered regarding the acceptance of this technology by vehicle drivers. In this study, the authors aim to investigate the factors influencing drivers' acceptance of using electric vehicles for LMD of small and medium-sized parcels, utilizing the Technology Acceptance Model (TAM), which is one of the most commonly used models for understanding the acceptance of a technology by individuals. The study also aims to provide a comprehensive literature review on the subject. In addition to the core TAM variables, the study incorporates the independent variables of environmental concern and enjoyment into the conceptual model. It is expected that exploring the relationships between these added variables and intentions will contribute to the existing LMD literature. This is the first attempt to investigate this topic in Turkiye. This study also represents a research agenda on this topic and offers broad research opportunities for the future. Moreover, it helps stakeholders better understand the factors that influence e-vehicle adoption for last-mile parcel delivery from the perspective of drivers and therefore encourages the development of industry use.

E-VEHICLES AND ITS USAGE IN LMD

The increase in e-commerce has led to a rise in last-mile package deliveries, primarily in urban areas, negatively impacting environmental, economic, and social sustainability. There are several innovative alternatives available to address these problems, such as reception boxes, crowdshipping, trunk delivery, cargo bikes, pick-up points, underground delivery, scooters, parcel lockers, robots (bots), e-vehicles, drones, home access systems, autonomous vehicles, combined with people transportation [Ulmer and Streng 2019, Wang et al. 2014, Carbone et al. 2017, Devari et al. 2017, Dorling et al. 2016, Murray and Chu 2015, Slabinac 2015, Reyes et al. 2017].

Although the use of fully or partially electric vehicles that produce zero emissions, have low noise levels, and operate on batteries is still in its infancy for commercial transportation and distribution, they are considered a good solution in the context of environmental sustainability [Saldaña et al. 2019, Quak et al., 2016, Nicolaides et al. 2017, Anosike et al. 2021]. [Kijewska et al. 2016] and [Bandeira et al. 2019] emphasize electric vehicles and electromobility as one of the best alternatives for addressing issues related to emissions from conventional fuels. Fully electric vehicles have great potential for reducing externalities associated with LMD in the near future [Ranieri et al. 2018]. Electric hybrid and fuel cell electric vehicles (FCEVs) are lightweight, agile, environmentally friendly, highly mobile, low-noise, and require less space for parking, making them suitable for transporting small packages. The main limitations of electric vehicles are their limited range (averaging about 150 km), the need for recharging, and long charging times. As a result, hybrid vehicles with lower investment costs and higher autonomy are currently more preferred [Ranieri et al. 2018]. Undoubtedly, the autonomy of vehicles, the location of charging points, and charging times are of great importance in using electric vehicles for LMD [Ranieri et al. 2018]. In addition to these factors, infrastructure (sufficiency of depot-based and public charging stations) and other operational barriers (driver training, fleet size decisions, topography, integration of limited range and charging station location into routing problems) can pose challenges relating to the adoption of this technology [Anosike et al. 2021, Christensen et al. 2017, Guo et al. 2018].

There are various studies in the academic literature regarding the use of electric vehicles for LMD. Oliviera et al. (2017) established that the use of zero-emission electric vehicles in last-mile distribution can reduce the negative impacts of traditional transportation and facilitate the transition to an efficient new transportation infrastructure. Bandeira et al. (2019) conducted a study focused on Brazil, indicating that the use of electric three-wheeled bicycles for LMD is a more suitable alternative in economic, environmental, and social aspects, and it does not require public incentives. Kijewska et al. (2016) highlighted electric vehicles as one of the best alternatives for addressing issues related to emissions from conventional fuels, focusing on practical applications within the EUFAL (Electric urban freight and logistics) project. Schröder (2017) mentioned that the use of electric vehicles in LMD can lead to cost savings in operations, emphasizing that the technical and economic benefits of electric vehicles in last-mile distribution will increase depending on technological, political, and market demand developments.

STUDIES ON USERS' ACCEPTANCE OF E-VEHICLES

From the Industrial Revolution to the present, many technologies have emerged that have made human life easier. However, new technologies have also brought along some environmental issues [Wu et al. 2019]. In particular, global warming and CO2 emissions have made it necessary for governments and companies to act more sensitively [Shanmugavel and Micheal 2022]. In this context, investments in renewable energy have increased to ensure sustainability and protect the future of the world, making the use of environmentally friendly electric vehicles more essential than ever [Shanmugavel et al. 2022]. In this regard, it is predicted that electric vehicles, autonomous vehicles and drone technology will advance in the future, and with the constructive policies of governments, their market share will increase [Wang et al. 2022]. Within this scope, investigating the attitudes and intentions of potential users towards electric vehicles is of great importance. Although there are limited studies in the literature regarding consumer acceptance of using electric vehicles for LMD, no studies have been found specifically addressing driver acceptance. [Wikstrom, Hansson and Alvfors 2016] emphasized that user acceptance is the most crucial factor in the successful adoption of electric vehicles. [Anosike et al. 2021] researched the challenges and evaluated the potential of adopting electric vehicles for last-mile package deliveries. It was indicated that companies using these vehicles will face difficulties related to fleet size, delivery schedules, and capacity. Shanmugavel and Micheal (2022) conducted a study with 402 participants, adding different variables to the Technology Acceptance Model (TAM) to investigate the relationships between consumers' behavior, attitude, and intentions in the context of electric vehicle usage. The findings demonstrate that all marketing activities and incentive opportunities significantly influence the intention to purchase electric vehicles. Shanmugavel et al. (2022) examined the acceptance processes and influencing factors of electric vehicle usage with the participation of 400 individuals using the TAM. Structural Equation Modeling (SEM) was used in the analysis. The findings indicated significant relationships between the included variables and intention. A mediating effect was found between Perceived Usefulness (PU) and Intention (I), and furthermore, age, income, and gender were found to have a positive moderating effect on the relationships between PU and I. In a study involving 232 participants, Dudenhöffer (2013) emphasized that inadequate information provision would lead to failure in the acceptance of electric vehicles by end users. Analysis conducted using Partial Least Squares Structural Equation Modeling (PLS-SEM) yielded different results from the TAM literature. Wu et al. (2019) investigated factors influencing the acceptance of electric and autonomous vehicles by potential users in the context of environmental benefits. The analysis in that study was conducted using TAM and SEM. The findings showed a positive relationship between PU, Perceived Ease of Use (POUE), Environmental Concern (EC), and Intention (I). Tu and Yang (2019) examined individuals' intentions to purchase electric vehicles and the influencing factors within the framework of TAM, Theory of Planned Behavior (TPB), and Innovation Diffusion Theory (IDT). The analysis in their study, conducted using SEM, indicated a positive relationship between Attitude Towards Use (AT) and Intention (I) with all variables except the Product Innovativeness (PI) variable. Ngoc et al. (2023) investigated the factors influencing the acceptance of electric vehicle usage for LMD using TAM and data obtained from individuals residing in Vietnam. The findings showed no significant relationship between I and the variables PU and Perceived Risks (PR), but the results of other hypothesis tests were consistent with the literature. Studies conducted on this subject using TAM and their findings are summarized in Table 1.

THEORETICAL FRAMEWORK AND HYPOTHESIS DEVELOPMENT

Davis (1986) based his work on the Theory of Reasoned Action (TRA) and proposed the Technology Acceptance Model (TAM), which incorporates the variables Perceived Usefulness (PU) and Perceived Ease of Use (PEOU), to investigate the factors influencing the usage processes of new technologies. TAM has been widely used in the context of the acceptance of new technologies. TRA focuses on studying people's general behavior, while TAM is more concerned with individuals' attitudes and intentions towards technological products and services [Davis 1989]. According to Ajzen and Fishbein (2005), the most important factor influencing individuals' adoption of a new technology is their intention to engage in that behavior. Intention (I) is considered a prerequisite for any behavior [Venkatesh and Davis 2000]. The stronger an individual's intention, the more likely their behavior is expected to change. In this regard, active behavior increases the likelihood of using new technologies [Davis, 1989; Venkatesh and Davis 1996]. The main variables in TAM, Perceived Usefulness (PU), Perceived Ease of Use (PEOU), and Attitude Towards Use (AT), are constructed to capture individuals' perceptions of new technologies [Davis et al. 1992]. PEOU refers to the belief that using the relevant technology will reduce the physical and mental effort required [Venkatesh and Davis 2000]. PU represents the degree to which users believe that using a specific system will enhance their job performance. AT reflects users' positive or negative thoughts and feelings towards the technology in question [Davis et al. 1992, Davis 1989]. Additionally, PEOU influences intention and attitude through PU (mediating variable). Attitude is considered an important determinant of intention [Venkatesh and Davis, 2000].

Based on all this information, in the current study, in addition to the core TAM variables, the concept model has included the variables Environment Concern (EC) and Enjoyment (E). The sub-dimensions of the hypotheses and their corresponding questions have been formulated in line with the literature [Ha and Janda 2012, Wu et al. 2019]. The hypotheses formulated are as follows:

The active usage processes of any technology can be predicted by individuals' intentions. When examining the adaptation processes for technologies with limited active usage, intention is included as a dependent variable in research models. In this regard, the relevant study focuses on intention as a precursor indicator of active usage [Tu and Yang 2019, Davis 1989, Ngoc et al. 2023, Venkatesh and Bala 2008, Toraman and Geçit, 2023]. Therefore, it is important to investigate the relationship between intention, which is considered an important determinant, and AT. Hence, the positive attitudes of EVs users towards the relevant technology will serve as a significant motivational factor for intention, which is a precursor to active usage. A conceptual model that guides this research and summarizes the hypotheses is presented in Figure 1.

Table 1. TAM Studies On Users' E- Vehicles Acceptance

Reference	Related Area	Hypothesis*	Result
Shanmugavel & Micheal (2022)	Usage of Electric Vehicles in City Logistics in India	PI→PU	Supported
		RPI→PU	Supported
		RPA→PU	Supported
		RP→PU	Supported
		PI→PU	Supported
		PIC→PU	Supported
		PU→I	Supported
Shanmugavel et al. (2022)	Usage of Electric Vehicles in City Logistics in India	II→PU	Supported
		VEI→PU	Supported
		PI→PU	Supported
		II→I	Supported
		VEI→I	Supported
		PI→I	Supported
		PU→I	Supported
Dudenhöffer (2013)	Usage of plug-in Electric Vehicles in City Logistics	PU→I	Not Supported
		PEOU→I	Not Supported
		PEOU→PU	Supported
		OU→I	Not Supported
		OU→PEOU	Supported
		SN→PU	Not Supported
		SN→I	Supported
Wu et al. (2019)	Usage of Autonomous Electric Vehicles in City Logistics	EC→PU	Supported
		EC→PEOU	Supported
		EC→I	Supported
		PEOU→PU	Supported
		PEOU→I	Supported
		PU→I	Supported
Tu & Yang (2019)	Usage of Electric Vehicles in City Logistics	PI→AT	Not Supported
		PC→AT	Supported
		PU→AT	Supported
		PEOU→AT	Supported
		SN→I	Supported
		AT→I	Supported
Ngoc et al. (2023)	Usage of Electric Cargo Vehicles in LMD	AT→I	Supported
		PEOU→PU	Supported
		PEOU→I	Supported
		PU→I	Not Supported
		PU→AT	Supported
		PR→PU	Not Supported
		PR→I	Supported
		PR→AT	Supported

*PU=Perceived Usefulness; PEOU=Perceived Ease of Use; PR=Perceived Risks; SN= Subjective Norms; SI=Social Influence; EC=Environmental Concern; PC=Perceived Compatibility; OU= Objective Usability; RPI = relative product innovativeness; RPA = relative product advantage; RP = relative price advantage; PIC = perceived incentives; PI = personal innovativeness; II=Information Influence; VEI=Value-expressive Influence, PI=Product, Innovativeness; I= Intention; AT= Attitude Towards Use.

Table 2. Hypotheses and Explanations

	Explanations
H1: Environment Concern (EC) affects the Perceived Usefulness (PU) to drive Electric Vehicles in last-mile parcel delivery.	EC is defined as the attitude that people form towards environmental issues, which has increased with the rise of environmental problems [Wu et al. 2019]. In recent years, people have been inclined to choose more environmentally friendly businesses, products, and vehicles due to global environmental crises. Studies have shown that individuals who show sensitivity towards this issue exhibit environmentally friendly attitudes and behaviors. In this context, it is crucial to investigate the existence of a positive and significant relationship between EC and PU. [Minton and Rose 1997]. It is expected that individuals who prioritize environmental issues will be more willing to use EVs within the scope of LMD. This suggests that there may be a positive relationship between EC and PU.

H2: Environment Concern (EC) affects the Perceived Ease of Use (PEOU) to drive electric vehicles in last-mile parcel delivery.	EC is defined as the attitude that people form towards environmental issues, which has increased with the rise of environmental problems [Wu et al. 2019]. In recent years, people have been inclined to choose more environmentally friendly businesses, products, and vehicles due to global environmental crises. Studies have shown that individuals who show sensitivity towards this issue exhibit environmentally friendly attitudes and behaviors. In this context, it is crucial to investigate the existence of a positive and significant relationship between EC and PU. [Minton and Rose 1997]. It is expected that individuals who prioritize environmental issues will be more willing to use EVs within the scope of LMD. This suggests that there may be a positive relationship between EC and PU.
H3: Environment Concern (EC) affects the Intention (I) to drive Electric Vehicles in last-mile parcel delivery.	Individuals with a high level of awareness not only participate in environmental conservation activities but also prefer environmentally friendly alternatives in their product and service purchases [Kim and Choi 2005]. As mentioned in the previous paragraphs, PEOU represents the degree to which an individual believes that using new technologies in a specific domain requires less effort [Venkatesh and Morris 2000]. The positive attitudes of environmentally conscious drivers towards electric vehicles support the existence of a positive and significant relationship between EC and PEOU.
H4: Enjoyment (E) affects the Perceived Usefulness (PU) to drive Electric Vehicles in last-mile parcel delivery.	Considering those electric vehicles, which are the subject of the current study, have environmentally friendly technology, it is likely that their use in LMD services will be positively perceived by consumers. Additionally, drivers who have environmental concerns are expected to have a positive view towards using both an economical and environmentally friendly delivery vehicle. Taking into account the potential impact of drivers' environmental sensitivities on their perceptions, attitudes, and intentions, EC has been included in the conceptual model. In this context, it can be argued that there is a positive relationship between EC and I [Venkatesh and Morris 2000].
H5: Enjoyment (E) affects the Perceived Ease of Use (PEOU) to drive Electric Vehicles in last-mile parcel delivery.	Enjoyment refers to the degree to which individuals perceive the use of technology as enjoyable. In recent years, the notion of deriving pleasure from the use of emerging technologies has been recognized as an important factor [Lee et al. 2019]. Previous studies have shown mixed findings regarding the relationship between E and PU [Mun and Hwang 2003]. In this context, the current study has included the relationship between E and PU in the conceptual model to examine the association between these variables.
H6: Enjoyment (E) affects the Intention (I) to drive Electric Vehicles in last-mile parcel delivery.	It is known that individuals' beliefs about the enjoyment of new technologies influence PU through PEOU [Venkatesh 2000]. Therefore, in line with this understanding, Enjoyment (E) has been included in the conceptual model, assuming that it will have a direct and indirect relationship with PEOU [Mun and Hwang 2003, Lee et al. 2019]. In this context, the current study focuses on the relationship between PU and PEOU through the variable of Enjoyment in the context of electric vehicle (EV) drivers.
H7: Perceived Ease of Use (PEOU) affects the Perceived Usefulness (PU) to drive Electric Vehicles in last-mile parcel delivery.	In studies conducted within the TAM framework, the existence of a relationship between enjoyment and intention has been observed [Lee et al. 2019]. It is stated that Enjoyment positively influences individuals' intention to use technology [Davis et al. 1992, Venkatesh 2000]. In the current study, Enjoyment has been included in the conceptual model, considering its potential impact on drivers' intentions to use EVs.
H8: Perceived Ease of Use (PEOU) affects Attitude Towards Use (AT) to drive Electric Vehicles in last-mile parcel delivery. *H9: Perceived Usefulness (PU) affects Attitude Towards Use (AT) to drive Electric Vehicles in last-mile parcel delivery.*	As mentioned in the previous paragraph, PEOU represents the degree to which an individual believes that using a particular technology will require less effort. In this context, it is assumed that the belief in less effort will also influence PU. Previous studies have provided evidence for the existence of this relationship [Davis 1989, Wu et al. 2019].
H10: Attitude Towards Use (AT) affects Intention (I) to drive Electric Vehicles in last-mile parcel delivery.	Attitude Towards Use (AT) is related to individuals' positive or negative perceptions of new technologies. The most important determinants of AT towards technology usage are PU and PEOU. Previous studies have explained individuals' attitudes towards technological innovations through the variables of perceived usefulness and perceived ease of use [Cai et al., 2021]. In this context, it is expected that drivers' beliefs that using EVs in LMD processes will enhance their performance and will positively influence their attitude towards use. Additionally, drivers' beliefs that they will exert less effort in urban traffic are expected to positively impact their attitude [Wu et al. 2019]. Based on this information, hypotheses H8 and H9 have been formulated.

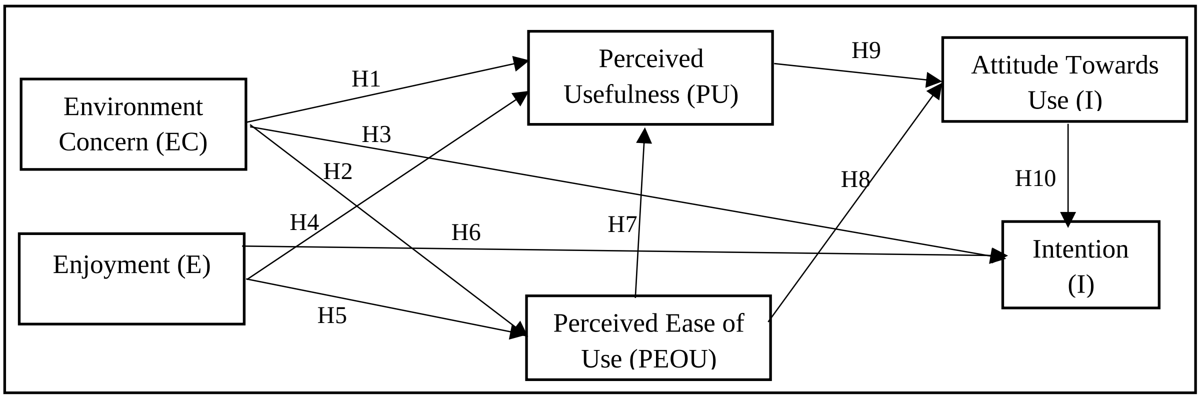

Fig. 1. Proposed Research Model.

RESEARCH METHODOLOGY AND DATA ANALYSIS

The authors created an online survey to collect data in order to empirically test the theoretical model and hypotheses. PLS-SEM was used to evaluate the measurement and structural models and test the assumed relationships between constructs. A 5-point Likert scale was used for responses, ranging from 1 = 'Strongly Disagree' to 5 = 'Strongly Agree'. The survey questions were developed in accordance with the items used in TAM studies. Sample data was collected in 2022 via online and face-to-face interviews. This study targeted drivers residing in Turkiye and working in different carrier firms who were involved in the LMD processes by driving vehicles. There are no formal statistics about the total number of drivers involved in the relevant processes. For this reason, the authors built samples using the most known 6 carrier firms working for B2C deliveries and a total of 180 responses were obtained. The findings obtained from the relevant participants are stated below.

Table 3. Descriptive Statistics of Respondents

Age	**No**	**%**
Under 21	30	16.7
21-29	105	58.3
30-39	25	13.9
40-49	15	8.3
50-59	-	-
60 and over	5	2.8
Total	**180**	**100**
Gender	**No**	**%**
Male	165	91.7
Female	15	8.3
Total	**180**	**100**
Income	**No**	**%**
5500 ₺ and under	40	22.2
5500 ₺ -7500 ₺	45	25
7501 ₺-9500 ₺	20	11.1
9501 ₺-11500₺	35	19.4
11501 ₺ and over	40	22.2
Total	**180**	**100**
Education	**No**	**%**
Middle school	20	11.1
High school	80	44.4
Vocational school	30	16.7
4-year College Degree	30	16.7
Master's degree	20	11.1
Total	**180**	**100**

Table 3 presents the demographic characteristics of the participants in the study. The fact that only 8.3% of the participants were female can be explained by the predominance of male drivers in the industry. It can be inferred that young carriers are preferred in activities such as last-mile logistics, as 75% of the participants were below the age of 30. When examining the educational degrees of the participants, it can be observed that individuals with a high school diploma constitute the majority, accounting for 44%.

Table 4. Convergent validity, construct and indicator reliabilities

Items	Source adapted	Factor Loading	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
EC1 I think that drivers are responsible for the use of e-vehicles (EVs) in parcel delivery processes for environmental sustainability.	Wu *et al.*, 2019; Müller, 2019; Wang *et al.*, 2020	0.853	0.755	0.859	0.670
EC2 I think that environmental problems have become more serious due to the use of internal combustion engines.	Wu *et al.*, 2019; Müller, 2019; Wang *et al.*, 2020	0.815			
EC3 I consider the environmental consequences when choosing the delivery vehicle type in parcel delivery processes.	Wu *et al.*, 2019; Müller, 2019; Wang *et al.*, 2020	0.328			
EC4 I think we should live in harmony with the environment by using EVs in last-mile parcel delivery processes to ensure sustainability.	Wu *et al.*, 2019; Müller, 2019; Wang *et al.*, 2020	0.785			
E1 Driving the EVs to be enjoyable in last-mile parcel delivery.	Lee *et al.*, 2019; Mun & Hwang 2003; Venkatesh, 2000	0.804	0.756	0.862	0.678
E2 Driving the EVs is pleasant in last-mile parcel delivery.	Lee *et al.*, 2019; Mun & Hwang 2003; Venkatesh, 2000	0.934			
E3 I have a fun driving the EVs in last-mile parcel delivery.	Lee *et al.*, 2019; Mun & Hwang 2003; Venkatesh, 2000	0.719			
PU1 Driving the EVs improves my performance in last-mile parcel delivery.	Venkatesh, 2000; Michels *et al.*, 2021	0.783	0.869	0.910	0.718
PU2 Driving the EVs.increases my productivity in last-mile parcel delivery.	Venkatesh, 2000; Michels *et al.*, 2021	0.923			
PU3 Driving the EVs enhances my effectiveness in last-mile parcel delivery.	Venkatesh, 2000; Michels *et al.*, 2021	0.769			
PU4 I find the EVs to be useful in last mile parcel delivery.	Venkatesh, 2000; Michels *et al.*, 2021	0.903			
PEOU1 My interaction with the EVs is clear and understandable.	Venkatesh, 2000; Michels *et al.*, 2021; Davis *et al.*, 1989	0.898	0.865	0.908	0.714
PEOU2 Interacting with the EVs does not require a lot of my mental effort.	Venkatesh, 2000; Michels *et al.*, 2021; Davis *et al.*, 1989	0.804			
PEOU3 I find the EVs to be easy to drive in last-mile parcel delivery.	Venkatesh, 2000; Michels *et al.*, 2021; Davis *et al.*, 1989	0.892			
PEOU4 I find it easy to drive the EVs to do what I want it to do.	Venkatesh, 2000; Michels *et al.*, 2021; Davis *et al.*, 1989	0.779			
AT1 I like driving EVs in last-mile parcel delivery.	Cai et al., 2021; Davis *et al.*, 1989	0.905	0.869	0.920	0.793
AT2 I prefer driving EVs in last-mile parcel delivery.	Cai et al., 2021; Davis *et al.*, 1989	0.826			
AT3 I am glad that I have the option of driving the EVs in last-mile parcel delivery.	Cai et al., 2021; Davis *et al.*, 1989	0.937			
I1 I intend to drive EVs in last-mile parcel delivery.	Venkatesh, 2000; Davis *et al.*, 1989; Lee et al., 2019	0.942	0.898	0.937	0.831
I2 I predict that I would drive EVs in last-mile parcel delivery.	Venkatesh, 2000; Davis *et al.*, 1989; Lee et al., 2019	0.867			
I3 I will drive EVs for last-mile parcel delivery in future	Venkatesh, 2000; Davis *et al.*, 1989; Lee et al., 2019	0.925			

The measurement model was tested for internal consistency and for convergent and discriminant validity. The measurement items have demonstrated high levels of internal consistency reliability. These values are shown in Table 4. The Cronbach's Alpha values, which are recommended to be above 0.70, range from 0.755 to 0.898. The composite reliability values, also recommended to be above 0.70, range from 0.859 to 0.937. The factor loadings values, recommended to be above 0.70, range from 0.719 to 0.942. The AVE (Average Variance Extracted) values, recommended to be above 0.50, range from 0.670 to 0.831. In conclusion, all variables in the proposed research model are reliable and valid in terms of reliability and validity [Hair et al. 2011, Fornell and Larcker 1981, Hair et al. 2020, Sarstedt et al. 2022].

Table 5: Discriminant Validity Analysis based on Fornell-Larcker Criterion

Items	**AT**	**E**	**EC**	**I**	**PEOU**	**PU**
AT	0.890					
E	0.716	0.842				
EC	0.667	0.610	0.884			
I	0.875	0.725	0.738	0.912		
PEOU	0.826	0.613	0.591	0.772	0.845	
PU	0.722	0.729	0.577	0.637	0.550	0.848

After conducting reliability and validity analysis of the research, a correlation analysis was performed using the Fornell-Larcker criteria. Correlation analysis provides information about the strength and direction of relationships between variables. The Fornell-Larcker criteria table is constructed by taking the square root of the AVE values. The results are shown in Table 5. As can be seen, the variables meet the requirement of having the highest correlation with themselves. The values in the Fornell-Larcker criteria table are consistent with the literature [Hair et al. 2020, Hair et al. 2011, Fornell and Larcker 1981, Hair et al. 2019].

Table 6. Outputs of Structural Model

Hypothesis	**Relation**	**Path Coefficient**	**t value**	**p value**	**<0.05 Hypothesis supported?**
H1	EC→PU*	0.045	0.384	0.701	Not Supported
H2	EC→PEOU***	0.447	3.719	0.000	Supported
H3	EC→I**	0.296	3.434	0.001	Supported
H4	E→PU***	0.594	6.434	0.000	Supported
H5	E→PEOU**	0.304	2.650	0.008	Supported
H6	E→I*	0.084	1.232	0.218	Not Supported
H7	PEOU→PU*	0.161	1.733	0.083	Not Supported
H8	PEOU→AT***	0.612	7.230	0.000	Supported
H9	PU→AT***	0.387	4.202	0.000	Supported
H10	AT→I***	0.621	8.283	0.000	Supported

Note: *p < .10; **p < .01; *** p < .001.

The research results are shown in Table 6. The hypothesized model was estimated based on bootstrapping. Of the 10 relationships tested, 7 were found to be significant at $p < 0.5$. EC had no influence on PU ($\beta = 0.045$, $p > 0.5$). EC had a positive effect on PEOU ($\beta = 0.447$, $p < 0.5$). EC had a positive effect on I ($\beta = 0.296$, $p < 0.5$). In addition, E had a positive effect on PU ($\beta = 0.594$, $p < 0.5$). E had a positive effect on PEOU ($\beta = 0.304$, $p < 0.5$). E had no influence on I ($\beta = 0.084$, $p > 0.5$). PEOU had no influence on PU ($\beta = 0.161$, $p > 0.5$). PEOU had a positive effect on AT ($\beta = 0.612$, $p < 0.5$). Finally, PU had a positive effect on AT ($\beta = 0.387$, $p < 0.5$). AT had a positive effect on I ($\beta = 0.621$, $p < 0.5$). The analyses indicate that parallel results were obtained with the PU and PEOU literature (Davis et al., 1992: Davis, 1989). The H1, H6 and H7 hypotheses were not supported. However, as can be seen in Table 7, AT fully mediated between PEOU and I. In this context, an indirect effect is observed between PEOU and I. In addition, an indirect effect is observed between EC and AT. However, as can be seen in Table 7, and PEOU was fully mediated between EC and AT.

Table 7. Indirect Effects

Relation	Path Coefficient	t value	p value
PEOU→AT→I***	0.380	5.812	0.000
EC→ PEOU→AT**	0.274	3.130	0.002

Note: *p <.10; **p <.01; *** p <.001.

The R^2 and $Radj^2$ values are presented in Table 8. Since the active use of electric vehicle technology in logistics processes is not widespread, the analysis of factors influencing drivers' usage intention was the focus of the research. Therefore, the R^2 and $Radj^2$ values related to intention were examined. The R^2 value for intention was found to be 0.856, and the $Radj^2$ value was 0.851.

Table 8: R^2 Values of Variables

Items	**R^2**	**$Radj^2$**
PU	0.542	0.526
PEOU	0.477	0.465
AT	0.787	0.782
I	0.856	0.851

Based on the R^2 value, it can be inferred that a significant portion of the factors influencing drivers' intention to use electric vehicles in the LMD process has been included in the research, considering the absence of active use. The analysis of the research model is shown in Figure 2 as the output of Smart PLS 4. Factor loadings and T statistics are important factors in reliability and validity analysis. Figure 2 illustrates the sub-dimensions of the variables and their corresponding factor loadings. Additionally, it presents the path coefficient (β) values and p-values indicating the acceptance of the research hypotheses. Finally, the summary includes the explanation percentages for the mediating and dependent variables, along with the R^2 values. A significant relationship was not found between EC and PU, E and I, and PEOU and PU, while all other hypotheses were accepted ($p < .05$).

CONCLUSIONS

Research shows that approximately 95% of parcel deliveries cover distances below 100 miles, which can be served effectively by zero-emission electric vehicles. The use of electric vehicles in the LMD, which presents various challenges in terms of energy efficiency and reducing environmental impact, is expected to have a revolutionary impact on reducing carbon footprints. In this context, identifying and understanding the factors that influence consumer acceptance, which is a determinant of market success, is of great importance for this technology. There are limited studies on factors influencing user acceptance in the literature, as well as a lack of research specifically focusing on factors influencing driver acceptance. This study examines the factors influencing driver acceptance of electric vehicles for LMD within the framework of the TAM. In addition to the core TAM variables, this study incorporates the independent variables of environmental concern and enjoyment. This research is the first to investigate the factors influencing driver acceptance of electric vehicle technology in parcel delivery specifically in Turkiye using the TAM framework.

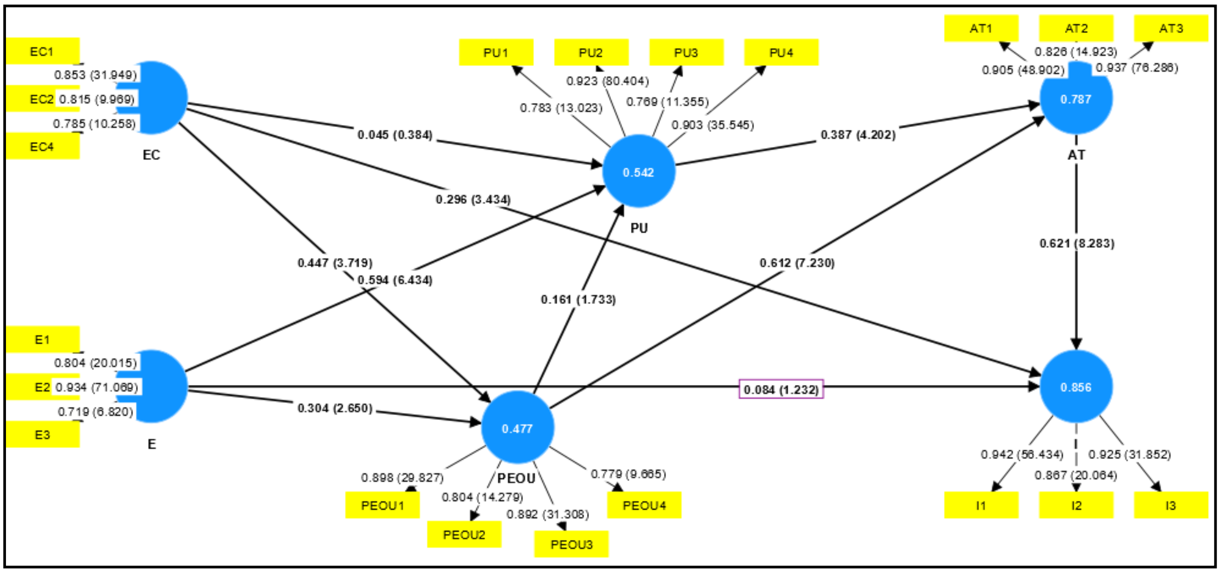

Fig. 2. PLS analysis results.

The findings of this study show that there is no direct significant and positive relationship between environmental concern and perceived usefulness. Similarly, there is no significant relationship between perceived ease of use and perceived usefulness of electric vehicle drivers. Additionally, the lack of a significant relationship between enjoyment and intention indicates that drivers may have different motivations in the delivery process rather than hedonic pleasures. The other hypotheses of the study have positive and significant relationships. When examining the indirect effects of environmental concern and perceived ease of use, it suggests that drivers may need time to fully embrace electric vehicles. As previously stated, due to the low rate of active usage, the focus of the current research is on drivers' intention to use electric vehicles. The relationships between the key factors influencing drivers' active usage (AT and I), parallel results with the literature are obtained. Therefore, identifying the factors influencing the use of electric vehicles will provide insights to future private institutions, organizations, and policymakers operating in this field.

Undoubtedly, the increasing integration and automation efforts among relevant parties, as well as the adaptation of vehicles for large-scale shipments, will contribute to the increased use of electric vehicles. In this context, technical issues related to electric vehicle delivery, as well as traffic regulations, should be planned soon, and real-life tests and pilot programs should be accelerated and expanded. Future studies can analyze urban logistics structures in different cities, evaluate the rationality of using relevant vehicles, assess the location selection for charging stations, and identify factors influencing user acceptance of this technology in different countries to make comparisons. Additionally, it should be noted that this study was limited to Turkiye, thus conditions in other countries may yield different findings. It should be acknowledged that the use of electric vehicles in the last-mile delivery process is still in the testing phase. As electric vehicles become more widely utilized in relevant processes, different factors can be added to the model or research can be expanded using different models.

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ORIGINAL PAPER

DIGITAL INTEROPERABILITY AND TRANSFORMATION USING INDUSTRY 4.0 TECHNOLOGIES IN THE DAIRY INDUSTRY: AN SLR AND BIBLIOMETRIC ANALYSIS

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ABSTRACT. Background: The dairy industry has gradually adopted cutting-edge technology in the past few years. This review explores the evolution and interventions of Artificial Intelligence (AI), Machine Learning (ML), and Industry 4.0 in the dairy industry through a systematic literature review and bibliometric analysis.
Methods: The Web of Science, Scopus, etc. databases were used for bibliometric analysis from 1999 to 2022 related to the role of technology in the dairy industry. Analysis shows the tremendous growth in technology adoption after 2015, including Industry 4.0, blockchain, and traceability, which have recently emerged in the dairy industry.
Results: The findings suggest that traceability, data management, environmental impacts, and dairy supply chain operations need further exploration. A technological intervention wheel has been generated based on findings from the dairy sector. The current analysis demonstrates that such a bibliometric analysis and a systematic study were previously missing in the dairy industry, especially in a technological context.
Conclusions: This review paves the way for future research on emerging technologies such as traceability, blockchain, and Industry 4.0 in the dairy industry. The impacts of technological intervention on the circular economy and sustainable practices in the dairy industry are a potential area of future research.

Keywords: Dairy industry, Industry 4.0 technologies, Internet-of-things (IoT), Technological interventions, Artificial intelligence (AI)

INTRODUCTION

Technology is crucial in addressing food safety and security issues in different food industry sectors. Inventions and advancing cutting-edge technologies have transformed the food industry in recent decades [Herrero et al., 2020]. Industry 4.0 and AI are the two most important technical aspects driving this revolution. Many other developments affect how AI handles the massive data gathered from IoT devices in real-time. The IoT is the core component in many organizations and industries, enabling and upgrading industries via big data [Hettiarachchi et al., 2022]. Numerous technological advancements have increased the pace of such developments, leading to what is sometimes called the fourth industrial transformation (also known as Industry 4.0), which has digitally changed numerous food industries and the dairy sector. Like other industries, the dairy industry was significantly transformed during the industrial revolution [Malik et al., 2022; Xu et al., 2018]. Industry 4.0 has already intervened in almost every digital, physical, and biological domain [Chapman et al., 2022; Koh et al., 2019; Maynard, 2015]. The existing literature includes “Artificial intelligence (AI), big data (BD), robotics, smart sensors, the Internet of Things (IoT), augmented reality, cybersecurity, and blockchain” technologies in the food industry [Hassoun, Aït-Kaddour, et al., 2022; Hassoun, Bekhit, et al., 2022]. From feed production to animal management, automated milking to milk

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processing, monitoring to planning and dairy optimization, the dairy industry has seen substantial growth in the use of technology. Over the past few decades, the dairy industry has become increasingly saturated, with new customer requirements putting further pressure on and adversely affecting frameworks [Remondino & Zanin, 2022]. The main factors affecting dairy are food life, modernization, population changes, a shift in consumer demand for healthy and customized products, and sustainable standards. The dairy industry still lacks modernization in the context of sustainability [Hopkins & Hawking, 2018; Jayarathna et al., 2021; Pal & Kant, 2019; Zafarzadeh et al., 2021], but it has witnessed technological intervention in the past few years. Currently, industry 4.0 adoption is necessary to optimize the dairy industry for sustainability [Crosson et al., 2010; Gharehyakheh et al., 2020]. The highly perishable nature of dairy products and shifting consumer demand pose serious challenges for the dairy industry in the context of increasing production [Ji et al., 2022]. Emerging technologies are essential to improve safety, quality, and traceability relative to traditional methods of dairy production [Akbar et al., 2020; Burke et al., 2016]. Recently, there has been an increase in the connectivity of dairy industry-specific advancements in technology. There was a dramatic increase in the use of technology during the pandemic [Majumdar et al., 2022]. Such technologies are constantly improving, and more information will be made available to industry. Critical data can enhance system efficiency and animal well-being and longevity [Lovarelli et al., 2020]. The precision livestock sector provides better effectiveness by monitoring animal well-being, production, and environmental impacts, such as carbon emissions and food traceability [Charlebois & Haratifar, 2015; Siddharth et al., 2021; Mor et al., 2021]. However, due to poor coordination between dairy stakeholders and its quantity and complexity, data is not always utilized effectively [Bahlo et al., 2019; Morota et al., 2018; Wolfert et al., 2017].

Furthermore, one important technique is expected to implement a constant process that relies on three states of the value data chain: information gathering, interconnection, and data processing [Chen et al., 2014]. These stages are expected to improve managerial decision-making and accuracy to increase productivity, efficiency, and profitability [Bronson & Knezevic, 2016]. Implementing big data approaches provides more valuable insights than traditional methods [Lioutas et al., 2021]. Industrial intervention in the dairy industry is recognized as essential for improving operational activities, reducing environmental impacts, increasing revenue growth, and introducing sustainable techniques [Cabrera & Fadul-Pacheco, 2021; Etherington et al., 1995].

This review paper includes a systematic and bibliometric analysis of the existing literature discussing the intervention of technologies such as AI and Industry 4.0 in the dairy industry. Section 2 briefly outlines the review methodology adopted by authors to conduct this review; section 3 features a descriptive analysis of existing literature related to the theme; section 4 provides the bibliometric analysis; and section 5 discusses the review findings critically, along with some potential technological interventions and challenges in the dairy industry. Future research directions are discussed in the conclusion.

REVIEW METHODOLOGY

There is significant information in scientific databases, but scholars, policy experts, and professionals cannot always access it. For researchers and policymakers, obtaining valuable information from these databases takes time [Jamwal et al., 2021]. Systematic and bibliographic approaches were used to address the research questions of this paper. In line with the suggestions of Denyer and Tranfield [2009], a five-phase process was used for this systematic review, which includes review planning, database selection, inclusion/exclusion criteria, analysis and synthesis, and review reporting, as shown in Figure 1.

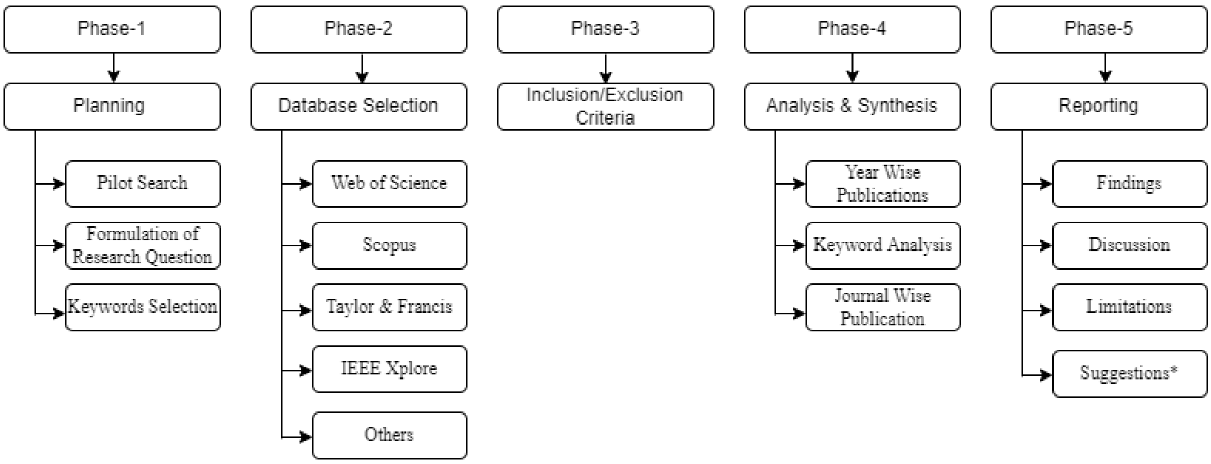

Fig. 1. Systematic review approach.

Planning Phase

As part of the review planning phase, the authors conducted a pilot search to understand the existing literature better and define inclusion/exclusion criteria. The primary goal of a systematic review is to properly formulate the research question, which leads to the selection of appropriate articles. The formulation of a research question, the selection of keywords, the selection of a database, and the use of well-defined inclusion/exclusion criteria all contribute to the flow of a systematic review. The main objective of this review is to explore the technological role of AI and Industry 4.0 in the dairy industry. The following research questions were formulated based on this review theme: 1) to explore the technological interventions of Industry 4.0 and digital technologies in the dairy industry; 2) to identify the interconnection between the dairy industry and Industry 4.0 or digital technologies.

The goal of research question 1 is to examine the existing literature to determine which technologies based on AI and IoT are used in the dairy industry. The second research question identifies the benefits of technologies, challenges, and future directions that will assist practitioners and researchers alike. The authors searched for articles in various scientific databases using the keywords “dairy industry,” “AI,” “IoT,” “dairy,” and “Industry 4.0.” The search queries ("industry 4.0" OR "artificial intelligence" OR "Blockchain" OR "Internet of things" OR "IoT" OR "machine learning") and ("dairy industry" OR "dairy") were used.

Selection of databases and keywords

The authors searched for relevant studies in various databases in the second phase. The authors selected Web of Science, Scopus, IEEE Xplore, Taylor & Francis, Wiley, and other reputable databases. The authors also used snowballing and back-referencing to select some articles. Databases were searched by adding search strings to the title, abstract, and keywords sections. The authors used the following keywords: Industry 4.0, the dairy industry, digital technology, and AI.

Inclusion/Exclusion criteria

The authors included articles related to technologies focused on the dairy industry. Only articles published in English and whose full text was available were considered for review. The authors only considered articles on technological intervention and adoption in the dairy industry.

Analysis and Synthesis/analysis method or tool used

Initially, the authors retrieved 571 articles from the selected databases. After applying the inclusion and exclusion criteria, which included full access, 376 articles were identified. The screening revealed that some articles were duplicates, and some were unrelated to the dairy industry or technological interventions, leaving only 102 articles for the final review and analysis. Descriptive statistics were used to analyze the literature. VOS Viewer and Biblioshiny library in R-studio were used for bibliographic analysis (both software applications are open access). The Biblioshiny library was used in R studio for word analysis, trends analysis, and to generate a thematic map. Vosviewer was used to analyze the co-occurrence of keywords and for cluster analysis.

RESULTS

Descriptive Statistics

This analysis aims to present the most relevant features of the selected literature, focusing on aspects related to the technological intervention of AI and Industry 4.0 in the dairy industry. The aspects considered are the latest trends related to technology in research publications, the evolution of technological intervention in the dairy industry, annual publications on related themes, the types of articles, and the journals that most frequently published articles on these topics.

Trends of publication time

Technological interventions involving AI and Industry 4.0 have been observed recently in the dairy industry. Figure 2 shows the trend in publications in the dairy industry over the past few years. Significant growth in the dairy industry can be seen after 2015, especially in the technological context. The trend indicates the increasing attention of industries and researchers toward digitalization in the dairy industry by using Industry 4.0 and digital technologies.

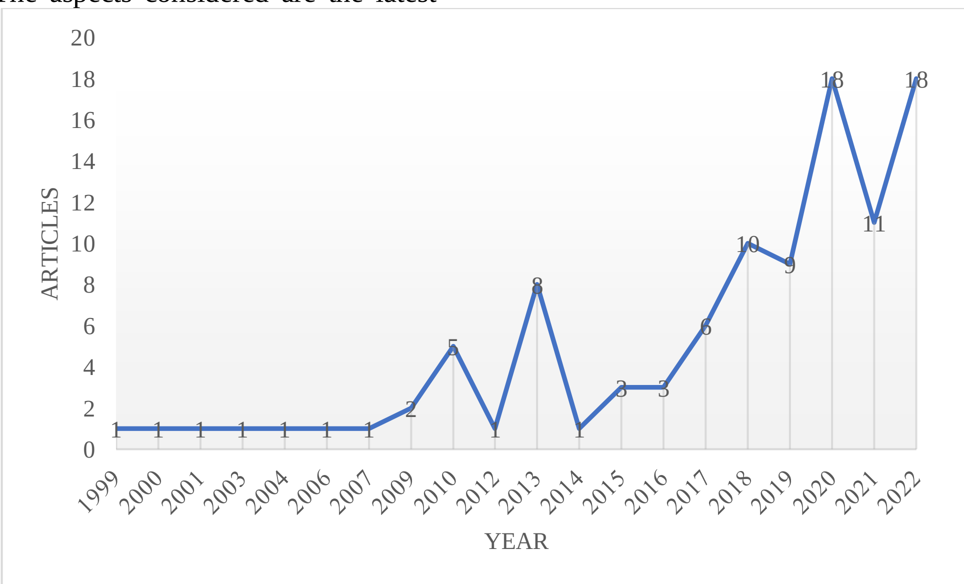

Fig. 2. Trends related to technology in research publications.

The number of publications is directly proportional to the increasing interest of researchers in emerging research areas related to technologies for various tasks, such as safety, security, efficiency, and management.

Evolution of Industry 4.0 technologies in the dairy industry

This analysis indicates the trend in the dairy industry's usage or implementation of different Industry 4.0 and digital technologies. Figure 3 depicts the evolution of Industry 4.0 and digital technologies and reveals a distinguishable increase in technological adoption after 2007. Since 2015, there has been an exponential increase in the adoption of these technologies. Among others, Industry 4.0 and Blockchain technology are dominant.

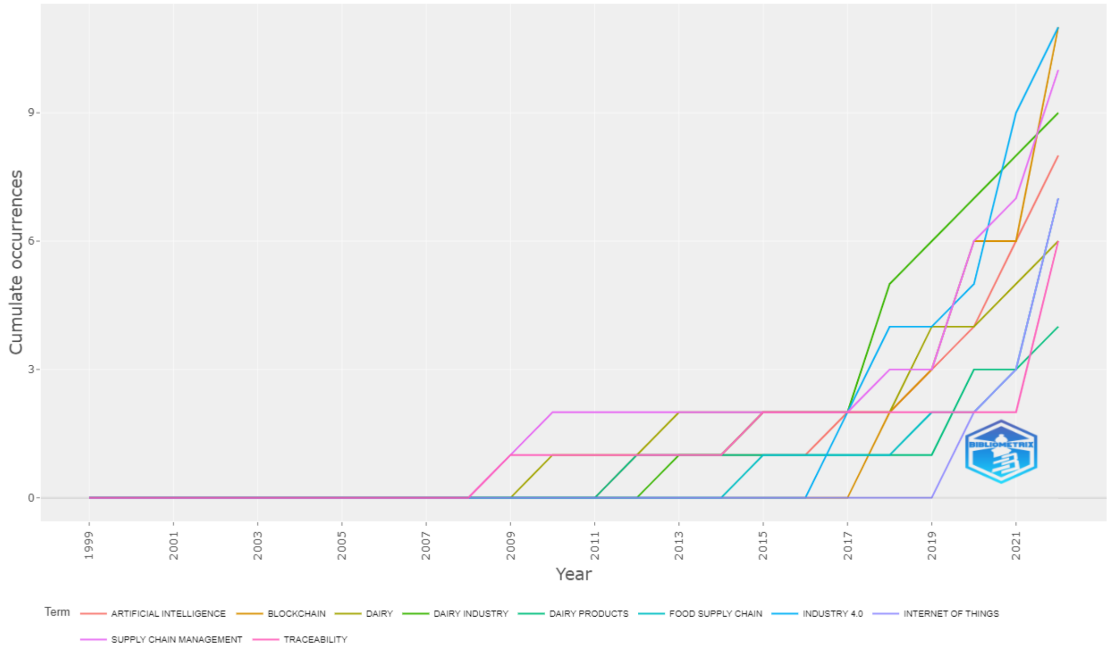

Fig. 3. Growth in technology adoption in the dairy industry.

Figure 3 depicts the cumulative occurrence of the most commonly used keywords in the recent literature, such as Industry 4.0, Blockchain, AI, the dairy industry, and traceability. It indicates that researchers are becoming more interested in technological applications in the dairy sector.

Journals that featured the most articles

The selected articles were published in 66 different journals. Figure 4 shows the journals that featured the most publications. Overall, the *Journal of Dairy Science* featured the most articles related to the research theme (only the top journals are listed).

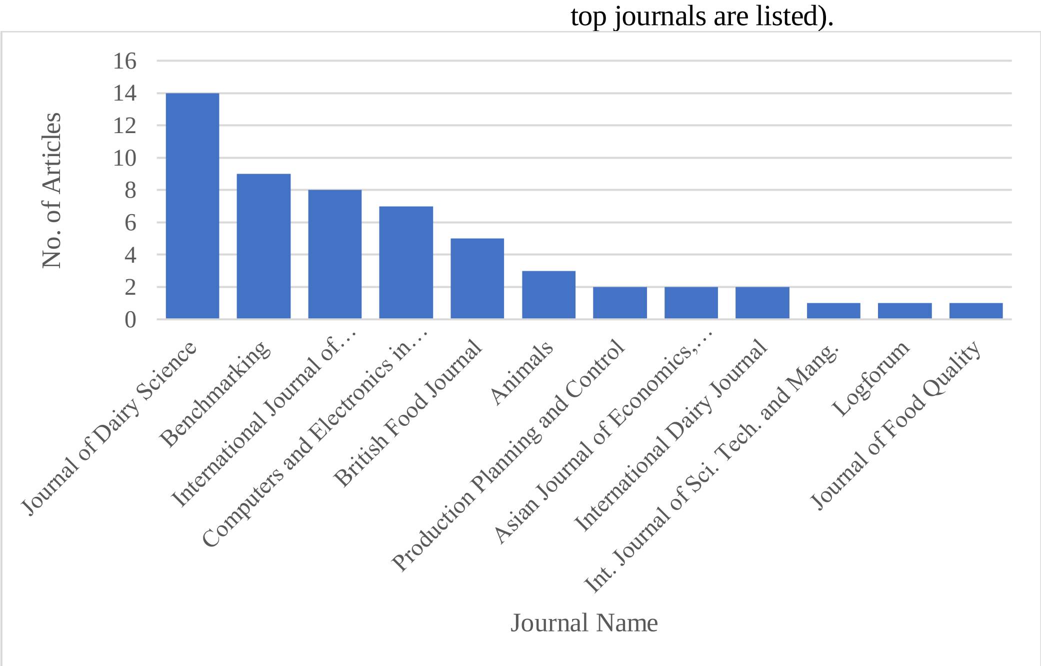

Fig. 4. Journals featuring the most articles on the research theme.

Benchmarking, the *International Journal of Production Research* and *Computers and Electronics in Agriculture* are leading journals with publications related to technological applications in the dairy industry.

Bibliometric Analysis

This section explores the most common themes discussed in the articles selected for the review. The authors analyzed the keywords used by the authors in the selected articles. This analysis focuses on the main themes related to technological interventions in the dairy industry and points toward the most used keywords. In previous research, researchers used different software applications for bibliometric analysis, each with its benefits and drawbacks [Jamwal et al., 2022].

Keywords co-occurrence

The co-occurrence of the keywords in the selected research articles is closely related to the theme of the review. Figure 5 shows the keyword analysis; this distribution demonstrates the popularity of various technological interventions in the dairy industry.

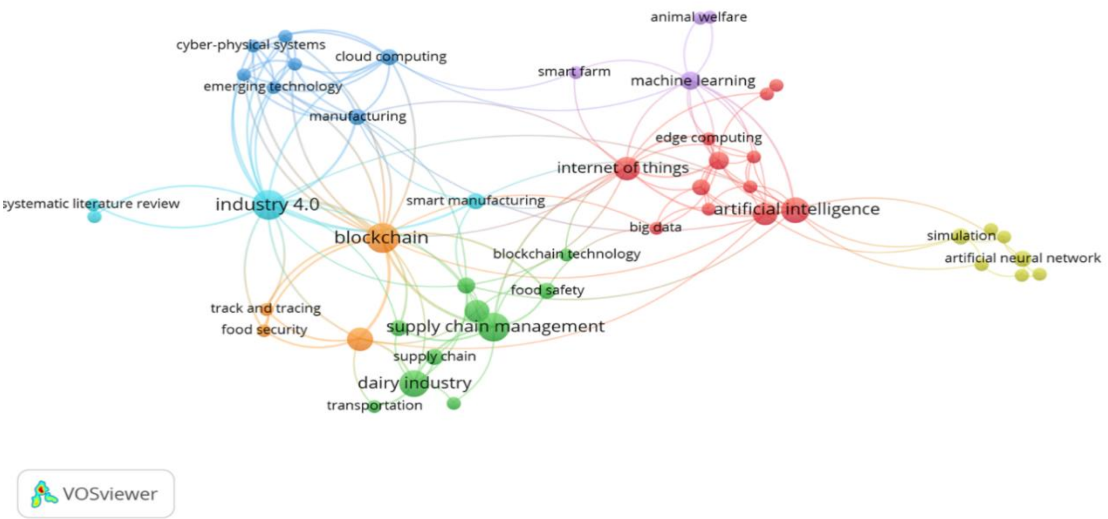

Fig. 5. Network of keywords analysis.

As shown in Figure 5, the "Industry 4.0" keyword is strongly associated with "blockchain," which is further strongly linked with "dairy industry" and "supply chain management." The keyword "Internet of Things" is strongly associated with "AI" and "machine learning." Industry 4.0, Blockchain, AI, and the dairy industry are the most prominent keywords in Figure 5.

Thematic Map Analysis

Figure 6 shows four quadrants: niche themes, motor themes, emerging or declining themes, and basic themes. Density and centrality parameters were used to characterize these themes. The importance of a given theme in the entire domain is represented by centrality, and its development or growth is measured by density [Cobo et al., 2011]. Each quadrant represents a different aspect related to the evolution of a given technology. The emerging or declining themes quadrant shows the deficient development of a theme in a given domain; simulation appears in this quadrant, indicating its relatively modest applicability in the dairy industry. Motor themes represent all the properly established themes in the given domain that are essential from a research point of view. Smart farms, artificial neural networks (ANN), AI, ML, and blockchain appear in this quadrant, which indicates their potential application in the dairy industry.

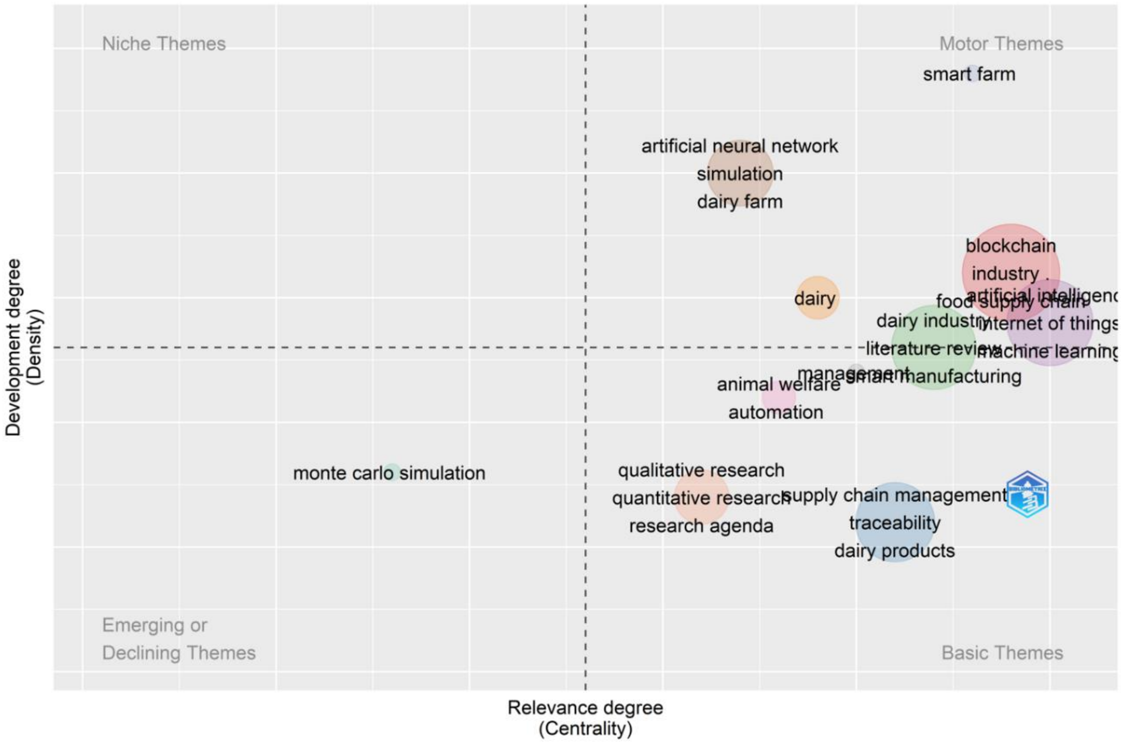

Fig. 6. Thematic analysis.

The basic theme quadrant features clusters essential to the given research field, which still need to be implemented and explored from a research point of view. The dairy industry still underutilizes traceability, automation, optimized supply chain management, and animal welfare.

Cluster analysis

Figure 5 presents seven clusters in the keyword network diagram represented by seven colors. Based on their connections, the authors categorize the keywords into seven clusters. Table 1 shows the seven identified clusters and the keywords associated with each cluster.

Although there were seven clusters, the authors merged clusters 2 and 7 as these both indicate the intervention of blockchain technology in the food safety and security context in the dairy industry.

1. The red cluster includes twelve keywords: AI, big data, the IoT, sensors, etc. These keywords indicate that this cluster's main topic is the exploration of digital interventions in the dairy industry.
2. The green and orange clusters include ten and four keywords, including blockchain technology, dairy industry, traceability, food safety, etc. These keywords indicate that the main topic of these clusters is the exploration of technological interventions in the context of traceability and food safety in the dairy industry.
3. The blue cluster includes seven keywords: cyber-physical system, cloud computation, industrial integration, IoT, etc. These keywords indicate that the main topic of this cluster is the exploration of technological interventions in the context of the industrial integration of technologies within the dairy industry.
4. The yellow cluster includes seven keywords: prediction, optimization, artificial neural network, dairy farms, etc. These keywords indicate that the main topic of this cluster is the exploration of industrial optimization in the dairy industry.

5. The purple cluster includes four keywords: animal welfare, automation, machine learning, and smart farms. These keywords indicate that the main topic of this cluster is the exploration of technological interventions in production and livestock cattle management in the dairy industry.

6. The light blue cluster includes four keywords: Industry 4.0, smart manufacturing, the fourth industrial revolution, and systematic review. These keywords indicate that the main topic of this cluster is the systematic exploration of technological interventions in the dairy industry in a manufacturing context.

Table 1. Clusters and associated keywords

No. of Cluster	List of Keywords
Cluster 1	• Artificial intelligence • Big data • Dairy • Data integration • Data Sharing • Edge computing • Internet of things • Management • Precision agriculture • Precision livestock farm • Sensors • Smart farming
Cluster 2	• Blockchain technology • Dairy industry • Decision making • Food safety • Smart contracts • Supply chain • Supply chain management • Sustainability • traceability
Cluster 3	• Cloud computing • Cyber-physical systems • Emerging technology • Industrial integration • Industrie 4.0 • IoT • Manufacturing
Cluster 4	• Artificial neural network • Dairy farm • Milk production • Modeling • Optimization • Prediction • Simulation
Cluster 5	• Animal welfare • Automation • Machine learning • Smart farm
Cluster 6	• Industry 4.0 • Smart manufacturing • Systematic literature review • Fourth industrial revolution
Cluster 7	• Blockchain • Food security • Food supply chain • Track and tracing

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DISCUSSION

Based on the seven clusters, the identified technologies in each cluster and their respective applications in the dairy industry are categorized in Table 2, which includes technological interventions based on all the discussed technologies in different areas of the dairy industry.

Table 2. Technological Interventions of Industry 4.0 and Digital Technologies

Themes	Identified Technologies	Applications	References
Cluster 1	• Artificial intelligence • Big data • Data integration • Edge computing • Internet of things	• Improved data management • Profit maximization • Cost Minimization • Data integration • Animal welfare • Real-time monitoring • Real-time data collection • Prediction • Smart framing	[Aamer et al., 2021; Cabrera et al., 2020; Chander et al., 2022; da Rosa Righi et al., 2020; Fuentes et al., 2020; Goli et al., 2019, 2021; Khademi, 2018; Michie et al., 2020; Newton et al., 2020; Rebelo et al., 2022; Satya & Chimakurthi, 2017; Zhou et al., 2022]
Clusters 2 & 7	• Blockchain technology • Smart contracts • traceability	• Data security • Data integrity • Food safety • Food Security • Transparency • Decentralized system • Increased visibility • Increased accountability • Direct supply chain management • Traceable supply chain • Smart decision making	[Casino et al., 2020; Cavite et al., 2022; Kasten, 2019; Kayikci et al., 2022; Khan et al., 2022; Khanna et al., 2022; Kher et al., 2010; Kumar & Kumar, 2020; Lee et al., 2013; León-Bravo et al., 2022; Mania et al., 2018; Manikas & Manos, 2009; Niya et al., 2021; Shingh et al., 2020; Srivastava & Dashora, 2022; Tan & Ngan, 2020; Varavallo et al., 2022; Yi et al., 2022; Zhou et al., 2022]
Cluster 3	• Cloud computing • Cyber-physical systems • Industrial integration • Industry 4.0 • IoT	• Data sharing • Product sorting • Product identification • Product handling • Monitoring • Animal health monitoring • Alerts • Automated packaging • Robotics	[Akbar et al., 2020; Alonso et al., 2020; Deshmukh & Kele, 2015; Jachimczyk et al., 2021; Jamwal, Agrawal, Sharma, & Giallanza, 2021; Kayikci et al., 2022; Liao et al., 2017; Xu et al., 2018; Zheng et al., 2021]
Cluster 4	• Artificial neural network • Modeling • Optimization • Prediction • Simulation	• Process optimization • Process simulations • Demand forecasting • Predictive maintenance • Cost and profit optimization • Route Planning	[Chaturvedi et al., 2013; da Rosa Righi et al., 2020; Dash et al., 2022; Fadul-Pacheco et al., 2021; Goli et al., 2019; Goyal & Goyal, 2012; Hosseinzadeh-Bandbafha et al., 2018; Kebreab et al., 2019; Khademi, 2018; Macciotta et al., 2000; Schulze et al., 2007; Sefeedpari et al., 2013; Shokri Dariyan et al., 2020]
Cluster 5	• Animal welfare • Automation • Machine learning	• Automatic milking • Automated feeding • Automated handling • Classification and sorting • Prediction • Animal monitoring • Diseases control • Behavior analysis	[Cockburn, 2020; Fadul-Pacheco et al., 2021; Gengler, 2019; Ji et al., 2022; Michie et al., 2020; Shine & Murphy, 2022; Taneja et al., 2020; Warner et al., 2020]
Cluster 6	• Industry 4.0 • Smart manufacturing	• Smart production • Systematic processes • Inventory management • Real-time analysis • Improved efficiency • Waste management • Smart sensing • Re-productions	[Borah, 2017; Cannas et al., 2020; Charlebois & Haratifar, 2015; Cleary et al., 1999; Crosson et al., 2010; Daftary, 2019; Fadul-Pacheco et al., 2022; Geary et al., 2010; Georgiadis et al., 2019; Khanal et al., 2010; Liberati & Zappavigna, 2009; Maldonado-Siman et al., 2013; Mor et al., 2018a, 2018b; Rutten et al., 2013; Sel et al., 2017; S. Sharma et al., 2021; Y. K. Sharma et al., 2019; St-Pierre & Jones, 2001]

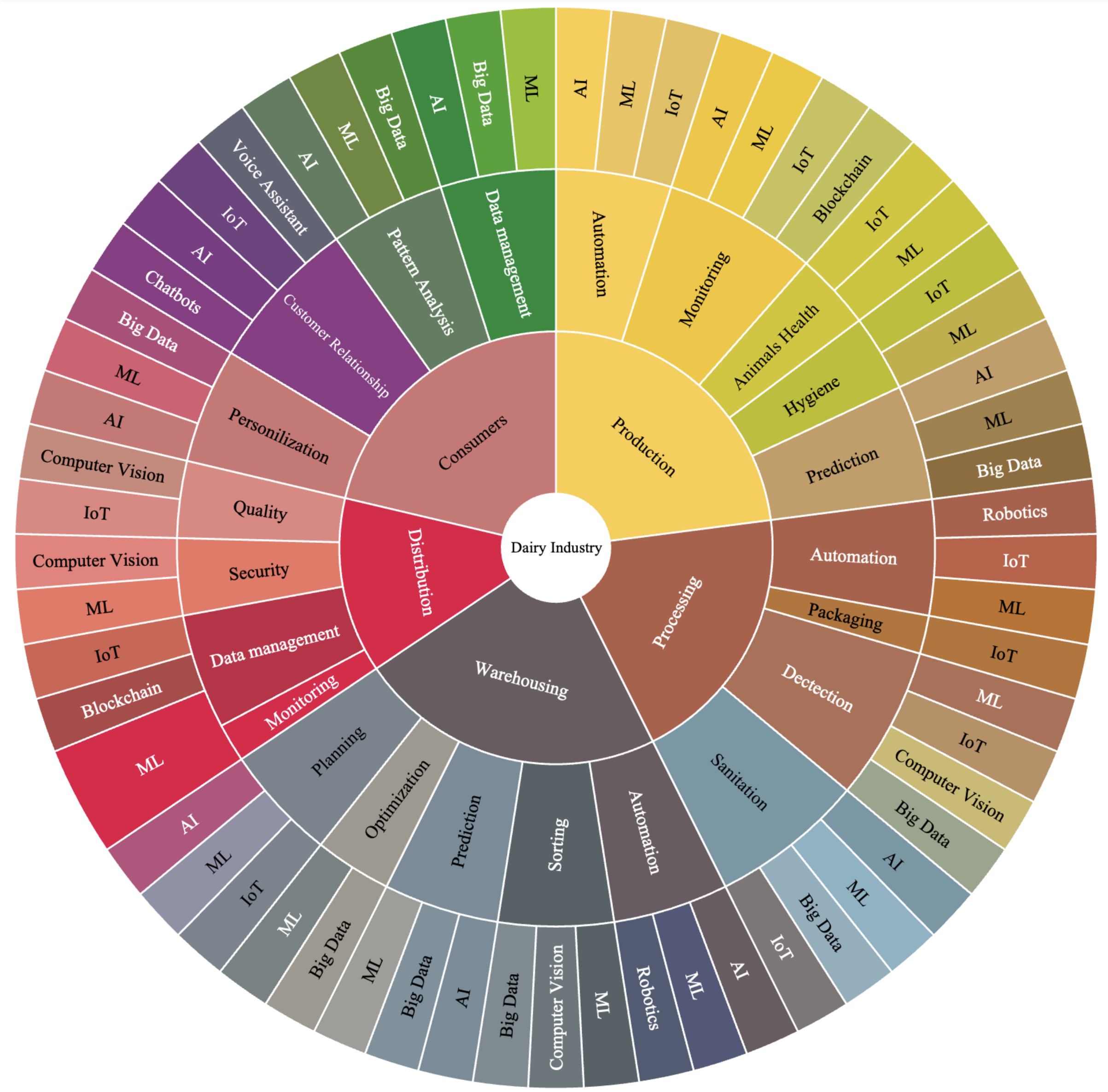

Fig. 7. Potential applications of technological adoption in the dairy industry.

Figure 7 provides a breakdown of dairy industry operations in different domains and the potential applications of Industry 4.0 technologies from farm to fork. Despite several applications, there are also drawbacks one should be aware of. The role of Industry 4.0 technology in sustainable practices in the dairy industry is still unexplored [Jamwal, Agrawal, Sharma, & Giallanza, 2021]. The same applies to other ingenious and intelligent technologies. It is well known that IoT and AI improve security measures but also introduce some flaws. Cyber-security is a risk for both beginners and professionals. Too much connectivity, mainly through IoT, can lay the groundwork for data leakage, loss of data, and hardware/network-based attacks. A second significant issue is technical complexity. These technologies involve many technical details that are challenging for the average employee to understand. Any power failure or software problem can cause the entire network to go down, generating substantial losses because the entire system is connected to its network by IoT devices. Industries have started using connected technologies to replace employees due to the growth and popularity of technology, which can lead to fewer job opportunities.

CONCLUSION

This review focused on technological interventions in the dairy industry, an emerging research domain. The status of the digital revolution in the dairy industry has been examined using a systematic and bibliographic approach. The authors conducted a bibliometric analysis of technological interventions in the dairy industry by selecting 102 articles published from 1999 to 2022. They utilized R studio, Microsoft Excel, and VOSviewer to generate informative statistics to analyze technological interventions in the dairy industry. Keyword analysis showed that Industry 4.0, blockchain, and AI were the most used keywords in the dairy industry. The review findings demonstrate the evolution of technology in the dairy industry, indicating the contribution of Industry 4.0.

The cluster analysis of potential technological applications within the dairy industry categorized them into different areas. The outcomes also indicate considerable scope for technological adoption on a larger scale to overcome the challenges related to food safety, security, and sustainability. The analysis, including traceability, animal welfare, and supply chain management, illustrated several promising research pathways. Further, this study can be extended domain-wise in the dairy industry to explore the most used technologies, such as Blockchain, IoT, and others, to address food safety, quality, and traceability-related issues.

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ORIGINAL PAPER

DELVING INTO THE NEXUS OF COLLABORATION AND SUPPLY CHAIN PERFORMANCE. EMPIRICAL EVIDENCE FROM AUTOMOTIVE INDUSTRY.

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ABSTRACT. Background: Supply chain management (SCM) practices play a significant role in modern business success through coordinating the continuous flow of goods, services and information within complex networks. At this level, the collaboration between supply chain (SC) members constitutes an important determinant of supply chain performance. Therefore, this study aims to explore the effect of supply chain collaboration dimensions, i.e., such as decision synchronization, collaborative communication, incentive alignment, goal congruence, information sharing joint knowledge creation, and resource sharing, on the level of supply chain performance.
Methods: The dataset was gathered using a convenience sampling procedure from middle and senior automotive SC executives. Partial least squares structural equation modeling (PLS-SEM) using SmartPLS software was carried out in order to analyze the data.
Results: The results show that collaborative communication, information sharing, incentive alignment, joint knowledge creation, and goal congruence contribute considerably to enhancing the automotive SC performance.
Conclusions: These findings have valuable implications for practitioners in order to adopt the appropriate practices to improve automotive SC performance. These insights can help to guide practitioners in implementing the appropriate collaborative practices to meet the specific challenges of the automotive supply chain. By considering these guidelines, practitioners will be able to streamline processes, optimize resource allocation and ultimately deliver more efficient outcomes, leading to improved overall automotive supply chain performance.

Keywords: Automotive industry, supply chain, collaboration, performance, structural equation modeling

INTRODUCTION

The Kingdom of Morocco has consolidated itself as the first automotive exporter on the African continent. The automotive industry is considered the largest exporting sector in Morocco. From 2014 to 2019, the industry generated over 147 000 direct jobs. This sector has recorded significant progress during the last decade. Today, the Kingdom of Morocco counts four main manufacturing hubs in Tangier, Kenitra, Rabat, and Casablanca, and numerous specialized automotive training centers, which offer significant business opportunities for multinational companies. Therefore, the kingdom expects to rank among the world's leading automobile manufacturers and to remain a competitive hub at the gateway to Europe.

Nowadays, worldwide competitiveness does not occur through individual enterprises but instead through supply chains [Farahani, et al. 2014]. Numerous players are involved in the automotive supply chain, which includes OEM automotive components, first-tier suppliers, 2nd-tier suppliers for component suppliers, and 3rd-tier suppliers for initial raw material suppliers, carriers, and distributors [Reddy et al. 2021].

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Supply chain collaboration has been a focus for researchers and practitioners considering the role of collaborative practices in the automotive supply chain. In this regard, collaborative approaches between the members of the supply chain have become a necessary condition for improving the performance level of the automotive supply chain. Hence, the purpose of this research is to investigate the role of collaborative practices between supply chain members in enhancing supply chain performance in the Moroccan automotive industry. More specifically, the goal of this study is to examine how various dimensions of SC collaboration, such as decision synchronization, collaborative communication, incentive alignment, goal congruence, information sharing joint knowledge creation, and resource sharing may influence SC performance.

As far as we know, this is the first empirical investigation of this topic in the Moroccan automotive industry. Hence, the research questions can be formulated as follows.

- How do collaborative practices in the automotive industry affect SC performance?
- Does sharing information and resource influence SC performance?
- Does goal congruence and decision synchronization promote the level of SC performance?
- Does collaborative communication, joint knowledge creation, and incentive alignment affect the automotive SC performance?

In order to answer these research questions, the current article is designed in the following order. Section 1 presents a review of the literature related to the relationship between collaborative practices between SC members and SC performance. The second section outlines the study methods. The presentation and the discussion of the results are outlined in the third section. Lastly, section 4 highlights the conclusions and suggests both theoretical and managerial implications.

THEORETICAL BACKGROUND

Supply chain collaboration is a major focus of management research [Al-Doori 2019; Cao Vonderembse, Zhang & Ragu-Nathan 2010; Ibn El Farouk, Moufad, Frichi, Arif & Jawab 2020; Ma, Wang & Chan 2020]. This concept reflects a "long-term partnership process where supply chain partners with common goals work closely together to achieve mutual advantages that are greater than the firms would achieve individually" [Cao et al., 2010].

It is recognized that supply chain collaboration positively and directly influences supply chain performance [Mofokeng & Chinomona 2019], which represents an essential condition for creating added value. The concept of supply chain performance is defined as "the ability of a supply chain to cost-effectively carry out its activities while minimizing costs, for the main purpose of meeting the ultimate customer's needs" [Mofokeng & Chinomona 2019].

Identifying key drivers of supply chain performance provides a basis for a successful supply chain [Boubker 2022; Chandak, Chandak & Dalpati 2021; Naoui, Boubker & Abdellaoui 2023]. Previous literature supports the essential contribution made by SC collaboration dimensions in enhancing the level of supply chain performance [García-Alcaraz et al. 2021]. According to Wiengarten et al. [2013], buyer-supplier collaboration is identified as a determinant of operational performance, more specifically, information sharing, incentive alignment, and joint knowledge creation are associated with improved performance under cost, quality, flexibility and innovativeness.

Several measurement scales have been adopted for operationalizing this multidimensional concept [Cao et al. 2010]. Researchers identify the following seven sub-components of supply chain collaboration, namely, goal congruence, information sharing, collaborative communication, joint knowledge creation, decision synchronization, incentive alignment, and resource sharing.

Information sharing (IS) reflects the degree to which a company exchanges a wide variety of pertinent, accurate, and timely information, plans, and procedures with its partners (Cao et al. 2010). Several empirical studies confirmed the significant influence of information sharing on SC performance [Adnani et al. 2023; Baah et al. 2021; Kankam et al. 2023; Whipple & Russell 2007]. For instance, the empirical study conducted by Al-Doori [2019] among SC members supports the direct and significant influence of information sharing and joint decision-making on operational performance. Furthermore, sharing information among partners in the supply chain can foster enhanced collaboration within the supply chain, leading to better operational performance [Fawcett, Wallin, Allred, Fawcett & Magnan 2011]. Tang et al. [2023] confirmed that sharing information and integrating customers significantly impacts on SC performance. In addition, García-Alcaraz et al. [2021] observed that the lack of sharing information between supply chain members is never translated into high SC performance. Hence, we suppose that:

Hypothesis 1. There is a significant impact of information sharing on SCP.

According to Zhang and Cao [2018], goal congruence (GC) represents "The process by which a firm perceives its own objectives are fulfilled by achieving the supply chain objectives." (p. 152). By investigating the influence of goal congruence, information sharing, and decision synchronization on SC performance among a population of 143 managers in different industrial sectors, García-Alcaraz et al. [2021] confirmed that the level of joint participation by SC members in conducting joint activities within a collaborative spirit helps to enhance SC performance. Hence, we suppose that:

Hypothesis 2. There is a significant impact of goal congruence on SCP.

Decision synchronization (DS) refers to the process of coordinating SC planning and operations decisions (i.e., strategy planning, production planning, order delivery, demand, and distribution management) that achieve optimal SC benefits [Simatupang & Sridharan, 2005]. Previous empirical investigations have shown a significant, direct and positive relationship between decision synchronization and SC performance [García-Alcaraz et al. 2021]. Hence, we suppose that:

Hypothesis 3. There is a significant impact of decision synchronization on SCP.

The incentive alignment (IA) represents the process for sharing risks, costs and benefits among SC partners [Cao et al. 2010]. A considerable body of literature has demonstrated the positive impact of incentive alignment on SC performance [Eriksson & Pesämaa 2007; Simatupang & Sridharan 2004]. By exploring the link between collaboration and supply chain performance of SMEs in Uganda, Eyaa et al. [2010] showed that incentive alignment as well as information sharing were key drivers of supply chain performance. Hence, we suppose that:

Hypothesis 4. There is a significant impact of incentive alignment on SCP.

The resource sharing (RS) refers to co-development of tools to assess performance of all SC members, as well as to share costs and risks that may occur in the supply chain [Paulraj, Lado & Chen 2008]. As a dimension of collaboration, resource sharing has been identified as a factor that favors collaborative advantage, in terms of process efficiency, flexibility, business synergy and quality innovation [Cao & Zhang 2011]. Hence, we suppose that:

Hypothesis 5. There is a significant impact of resource sharing on SCP.

The collaborative communication (CC) represents mechanisms for messaging between SC members regarding its frequency, direction, mode and strategy of influence [Paulraj et al. 2008]. Prior studies have shown that collaborative communication constitutes a relevant determinant of relational performance metrics [Chen et al. 2013]. As such, communicating efficiently between SC members leads to lower error associated with both product and performance, feeding into higher quality, better lead times and greater customer responsiveness [Chen et al. 2004]. Hence, we suppose that:

Hypothesis 6. There is a significant impact of collaborative communication on SCP.

Joint knowledge creation (JKC) relates to the process of jointly seeking and acquiring new and relevant knowledge, as well as assimilating and applying this knowledge. It also reflects efforts made by SC members to recognize clients' needs, discover emerging markets, and recognize competitors' capabilities [Jimenez-Jimenez, Martínez-Costa & Sanchez Rodriguez 2018]. The existing literature pointed out that joint knowledge creation significantly influences collaborative advantage by enhancing innovation, quality and efficiency [Uca et al. 2018]. Hence, we suppose that:

Hypothesis 7. There is a significant impact of joint knowledge creation on SCP.

Our proposed research model includes seven independent variables that served to measure supply chain collaboration, namely information sharing, decision synchronization, goal congruence, incentive alignment, resource sharing, collaborative communication, and knowledge creation (Fig. 1).

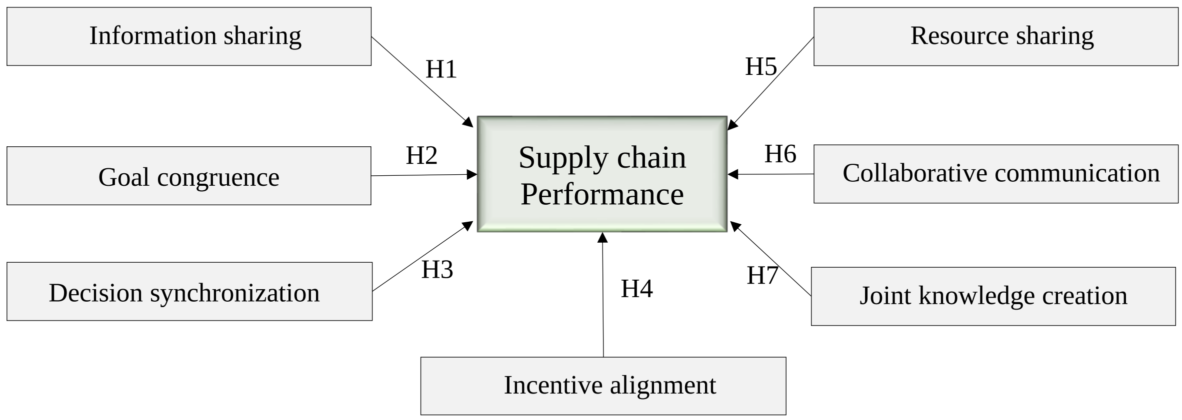

Fig. 1. Conceptual model.

MATERIALS AND METHODS

To generate items for measuring latent variables of the proposed model, we referred to earlier supply chain management studies. At this level, the supply chain collaboration was measured using seven sub-components, namely information sharing (IS - four items), goal congruence (GC: four items), decision synchronization (DS: four items), incentive alignment (IA: four items), resource sharing (RS: four items), collaborative communication (CC: four items), and joint knowledge creation (JKC: five items). All these measures were selected from the study by Cao and Zhang [2011].

The SC performance was assessed by four items selected from Qrunfleh and Tarafdar [2014]. This measurement scale includes the supply chain's ability to meet special customer specification requirements, the ability to adjust rapidly capacity to meet changes in customer demand, customer response time, short order-to-delivery cycle time. A five-point Likert-type scale was used for questions associated with each latent variable.

Since we have no database on all the automotive supply chain members in Morocco, a convenience sampling procedure was followed to gather data through a web-based questionnaire, by using a survey link to the target population via the LinkedIn platform. Convenience sampling was chosen due to practical considerations and limited resources [Sarstedt et al. 2018]. This method allowed for easy access to potential participants, as they were readily available and willing to participate in the study. However, it is important to acknowledge that the findings may not be representative of all supply chain members due to the non-random selection process. Data were gathered over a three-month period from February 2 to May 7, 2021.

As indicated in Fig. 2, the dataset was compiled from 95 middle and senior automotive supply chain executives, including more males (87.37%) than females (12.63%). Over half of those interviewed were aged between 26 and 36 years old (56.84%), with a large percentage holding a BAC+5 diploma (69.47%).

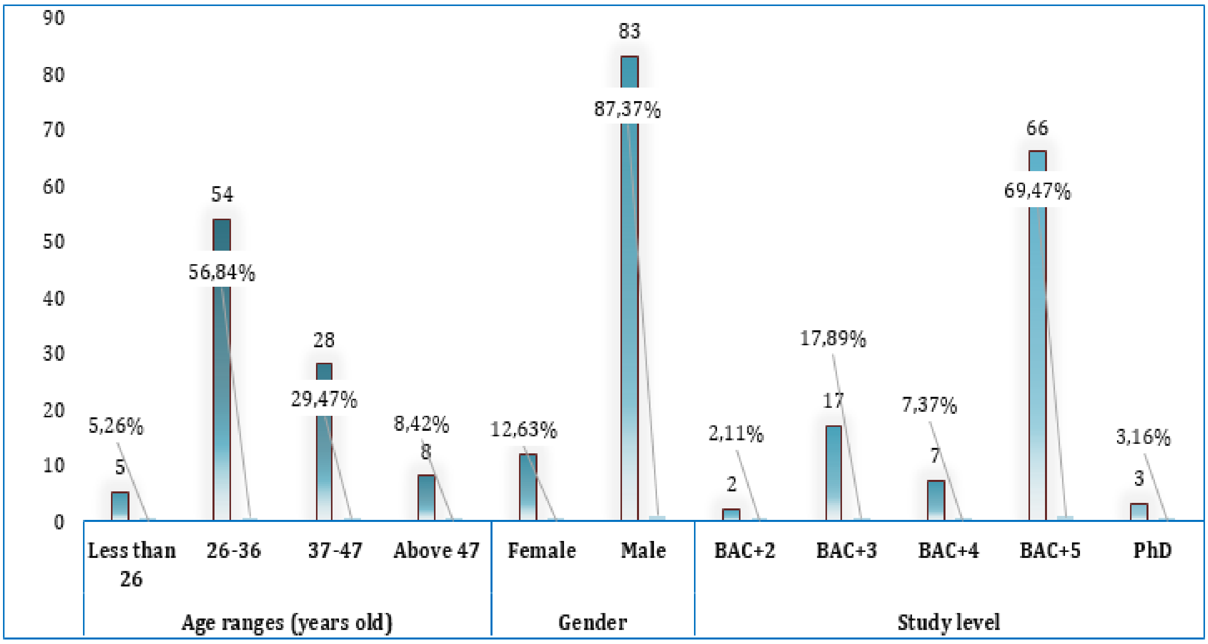

Fig. 2. Age, gender, and participants' study levels.

The data come from the SC manager (3.16%) logistics manager (24.21%), logistics coordinator (22.11%), logistics supervisor (17.89%), production planner (15.79%), procurement manager (8.42%), store manager (4.21%), and supply planner (4.21%). The majority of these participants in the survey have experience ranging from three to seven years (66.32%), more precisely 24.21 percent of them have experience ranging from three to five years and 42.11% of them have experienced five to seven years (Fig. 3). A large proportion of the survey participants are employees of automotive companies based in Tangier city (85.26%).

Regarding the data analysis methodology, we adopted a PLS-SEM procedure [Hair, Risher, Sarstedt & Ringle 2019]. As is the case in our study, the PLS-SEM is well suited to smaller sample sizes.

RESULTS

Measurement model validity

According to the data analysis performed using SmartPLS software, the items presenting a loading value lower than 0.7 were excluded from the model, these items are Res-Shar1, Dec-Syn3, and Go-Cong4, which have factorial contribution values of 0.47, 0.67, and 0.68, respectively (Fig. 4).

After removing items with a poor loading value, the results of the external model evaluation can be found in Table 1. The average variance extracted (AVE), Cronbach's alpha (α), and composite reliability (ρc) values are all above 0.5, 0.7, and 0.7, respectively, which ensures a good level of outer models' convergent validity.

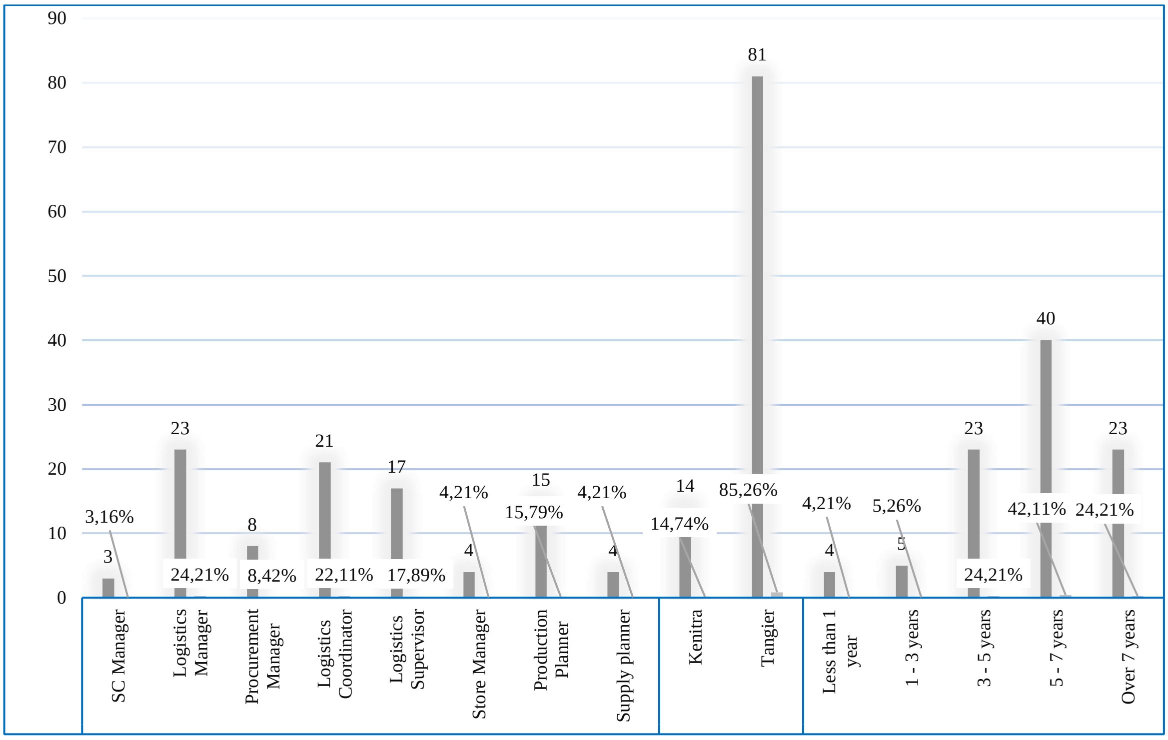

Fig. 3. Job title, city, and experience of study participants'.

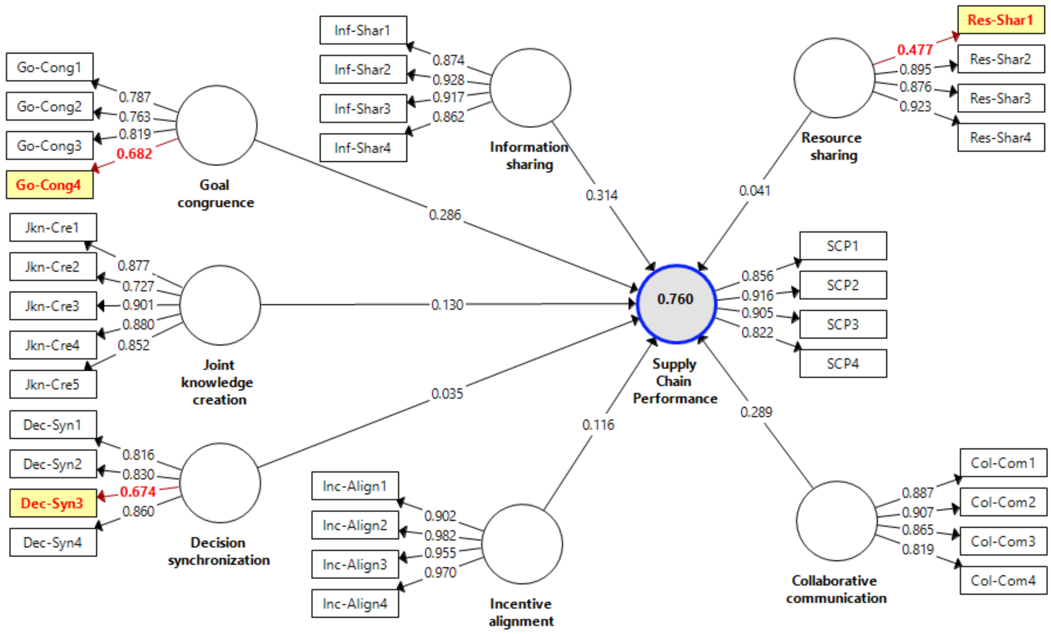

Fig. 4. Factor loadings results.

Table 1. Convergent validity results.

Convergent validity	CC	DS	GC	IA	IS	JKC	RS	SCP
Cronbach's alpha (α)	0.892	0.822	0.765	0.967	0.918	0.902	0.892	0.898
Composite Reliability (ρc)	0.926	0.893	0.862	0.975	0.942	0.928	0.928	0.929
Average variance extracted (AVE)	0.757	0.736	0.676	0.908	0.802	0.722	0.811	0.767

Furthermore, the discriminant validity is checked using the Fornell and Larcker criterion, and the Heterotrait-monotrait (HTMT) ratio, indicating that the greatest value of HTMT ratio is 0.895, which meets the specialists' recommendations [Henseler, Ringle & Sarstedt 2015]. Additionally, the discriminant validity of the outer model is assessed using cross-loading criterion, indicating that loadings of the indicators are greater than all its cross-loadings (Table 2).

Table 2. Discriminant validity results.

			CC	DS	GC	IA	IS	JKC	RS	SCP
Fornell-Larcker	Collaborative communication (CC)		0.870							
	Decision synchronization (DS)		0.597	0.858						
	Goal congruence (GC)		0.652	0.415	0.822					
	Incentive alignment (IA)		-0.307	-0.114	-0.268	0.953				
	Information sharing (IS)		0.808	0.561	0.522	-0.279	0.896			
	Joint knowledge creation (JKC)		0.582	0.488	0.413	-0.195	0.537	0.850		
	Resource sharing (RS)		0.238	0.120	0.108	-0.088	0.076	0.220	0.901	
	Supply chain performance (SCP)		0.802	0.603	0.667	-0.157	0.757	0.611	0.185	0.876
HTMT Criterion	Collaborative communication (CC)									
	Decision synchronization (DS)		0.699							
	Goal congruence (GC)		0.765	0.482						
	Incentive alignment (IA)		0.328	0.125	0.300					
	Information sharing (IS)		0.895	0.642	0.606	0.295				
	Joint knowledge creation (JKC)		0.647	0.567	0.489	0.202	0.593			
	Resource sharing (RS)		0.256	0.136	0.128	0.110	0.096	0.234		
	Supply chain performance (SCP)		0.888	0.694	0.789	0.160	0.827	0.681	0.185	
Cross-loadings	Collaborative communication (CC)	Col-Com1	0.89	0.43	0.59	-0.31	0.75	0.52	0.19	0.67
		Col-Com2	0.91	0.46	0.61	-0.35	0.76	0.58	0.24	0.72
		Col-Com3	0.86	0.58	0.59	-0.16	0.64	0.50	0.20	0.74
		Col-Com4	0.82	0.61	0.48	-0.25	0.65	0.42	0.19	0.65
	Decision synchronization (DS)	Dec-Syn1	0.45	0.84	0.42	-0.06	0.50	0.41	0.04	0.55
		Dec-Syn2	0.53	0.86	0.27	-0.16	0.40	0.45	0.14	0.46
		Dec-Syn4	0.56	0.88	0.36	-0.08	0.53	0.40	0.13	0.53
	Goal congruence (GC)	Go-Cong1	0.46	0.23	0.80	-0.17	0.38	0.36	0.10	0.47
		Go-Cong2	0.45	0.20	0.83	-0.24	0.31	0.25	0.01	0.49
		Go-Cong3	0.66	0.53	0.84	-0.24	0.56	0.39	0.14	0.65
	Incentive alignment (IA)	Inc-Align1	-0.27	-0.06	-0.21	0.90	-0.22	-0.11	-0.15	-0.09
		Inc-Align2	-0.28	-0.12	-0.26	0.98	-0.27	-0.20	-0.06	-0.16
		Inc-Align3	-0.34	-0.13	-0.29	0.96	-0.29	-0.21	-0.07	-0.18
		Inc-Align4	-0.26	-0.10	-0.24	0.97	-0.26	-0.20	-0.08	-0.13
	Information sharing (IS)	Inf-Shar1	0.74	0.51	0.52	-0.32	0.87	0.52	-0.02	0.59
		Inf-Shar2	0.73	0.45	0.47	-0.26	0.93	0.50	0.07	0.72
		Inf-Shar3	0.74	0.51	0.41	-0.20	0.92	0.46	0.13	0.70
		Inf-Shar4	0.68	0.55	0.47	-0.23	0.86	0.45	0.08	0.69
	Joint knowledge creation (JKC)	Jkn-Cre1	0.50	0.54	0.36	-0.14	0.46	0.88	0.20	0.53
		Jkn-Cre2	0.41	0.41	0.35	-0.07	0.38	0.73	0.17	0.52
		Jkn-Cre3	0.51	0.35	0.33	-0.25	0.46	0.90	0.19	0.51
		Jkn-Cre4	0.50	0.39	0.36	-0.20	0.46	0.88	0.19	0.51
		Jkn-Cre5	0.55	0.37	0.34	-0.16	0.52	0.85	0.19	0.52
	Resource sharing (RS)	Res-Shar2	0.20	0.08	0.12	-0.09	0.05	0.19	0.90	0.12
		Res-Shar3	0.18	0.00	0.09	-0.11	0.00	0.15	0.88	0.12
		Res-Shar4	0.24	0.18	0.09	-0.06	0.12	0.23	0.92	0.22
	Supply chain performance (SCP)	SCP1	0.75	0.62	0.58	-0.09	0.68	0.48	0.24	0.86
		SCP2	0.75	0.51	0.62	-0.20	0.67	0.54	0.20	0.92
		SCP3	0.75	0.54	0.55	-0.13	0.72	0.59	0.12	0.91
		SCP4	0.54	0.43	0.58	-0.12	0.57	0.54	0.07	0.82

Structural model assessment

Testing the inner model includes verifying multiple criteria, such as the coefficient of determination (R^2), the predictive relevance (Q^2), the effect size (f^2), and the goodness-of-fit. The study findings indicate that an R^2 value of SC performance is 0.757, indicating an appropriate degree of determination of this dependent variable (Fig. 5).

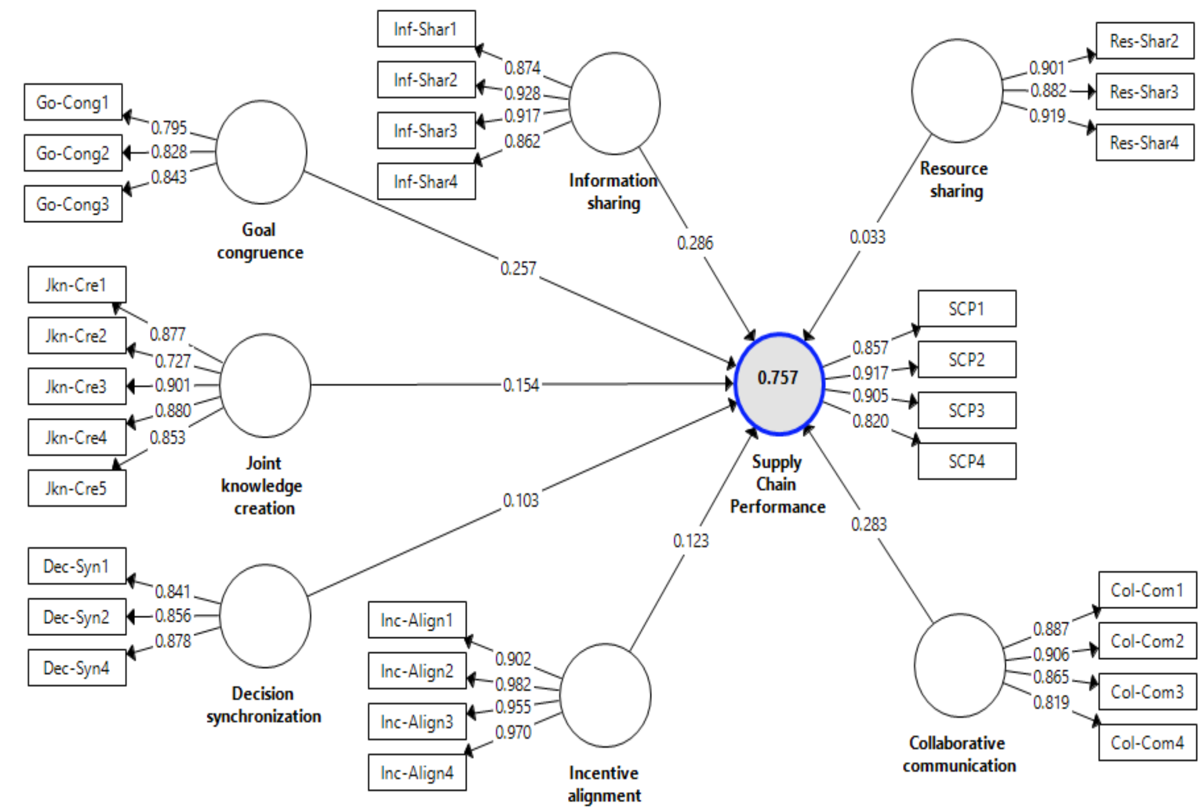

Fig. 5. Coefficient of determination of the Supply Chain performance.

As shown in Table 3, the Q^2 value for supply chain performance is greater than 0.39, which is 0.561, providing proof of the model's predictive relevance [Hair, Howard & Nitzl 2020]. Lastly, the GoF value is 0.76465, reflecting a large goodness-of-fit [Henseler, Ringle & Sinkovics 2009].

Table 3. Predictive relevance

Latent variable	**SSO**	**SSE**	**Q² (=1-SSE/SSO)**
Collaborative communication	380.000	380.000	
Decision synchronization	285.000	285.000	
Goal congruence	285.000	285.000	
Incentive alignment	380.000	380.000	
Information sharing	380.000	380.000	
Joint knowledge creation	475.000	475.000	
Resource sharing	285.000	285.000	
Supply chain performance	380.000	166.965	0.561

The results of hypotheses testing using SmartPLS reveal that under SC collaboration dimensions, information sharing (H1. β = 0.286, t = 2.582; p = 0.010), goal congruence (H2. β = 0.257, t = 3.638; p = 0.000), incentive alignment (H4. β = 0.123, t = 2.004; p = 0.046), collaborative communication (H6. β= 0.283, t = 2.551; p = 0.011), and joint knowledge creation (H7. β= 0.154, t = 2.463; p = 0.014) were found to have a positive influence on SC performance (Table 4).

Table 4. Results of hypothesis tests.

Hypothesis	β-value	Sample Mean	Standard Deviation	T-value	P-value	Effect size	Decision
H1. IS → SCP	0.286	0.279	0.111	2.582	0.010**	0.106	Supported
H2. GC → SCP	0.257	0.258	0.071	3.638	0.000***	0.153	Supported
H3. DS → SCP	0.103	0.104	0.077	1.332	0.184NS	0.026	Not supported
H4. IA → SCP	0.123	0.111	0.062	2.004	0.046*	0.055	Supported
H5. RS → SCP	0.033	0.040	0.061	0.537	0.591NS	0.004	Not supported
H6. CC → SCP	0.283	0.275	0.111	2.551	0.011*	0.076	Supported
H7. JKC → SCP	0.154	0.162	0.063	2.463	0.014*	0.060	Supported

*** $p < 0.001$; **$p < 0.01$; *$p < 0.05$. GoF = 0.764648857
Predictive relevance: Q^2 SCP = 0.561

The influence of decision synchronization (β= 0.103, t = 1.332; p = 0.184), and resource sharing (β= 0.033, t = 0.537; p = 0.591) on supply chain performance was found not significant, thereby H3 and H5 are not supported (Fig. 6).

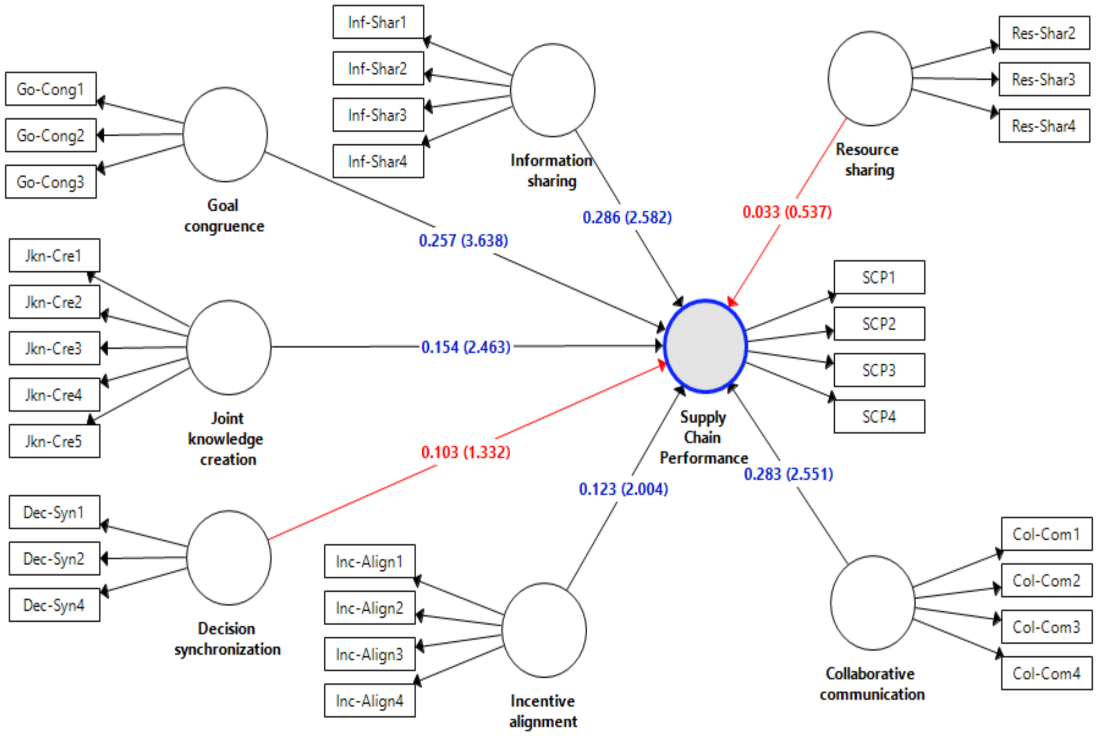

Fig. 6. Results of model testing.

DISCUSSIONS

The focus of this empirical investigation was to explore how collaborative practices between SC members affect automotive SC performance. More precisely, this study focuses on testing the impact of different dimensions of collaboration, including information sharing, goal congruence, incentive alignment, decision synchronization, collaborative communication, joint knowledge creation, and resource sharing on the level of SC performance. Hence, this study intended to bridge a knowledge gap in the SCM literature concerning the association between collaboration and performance.

The findings showed a positive and significant influence of information sharing on SC performance. In other words, when automotive SC members incorporate information sharing as part of their collaborative practices by exchanging timely, accurate, complete, and confidential information, they will help to enhance their supply chain's performance. These results are in line with earlier empirical studies in the area of SCM, which suggest that information sharing plays a significant part in enhancing competitive gains and SC performance [Adnani et al. 2023; Baah et al. 2021; Kankam et al. 2023; Whipple & Russell 2007]. García-Alcaraz et al. [2021] demonstrated empirically that a lack of information sharing is never linked to high performance across the supply chain. Likewise, Tang et al. [2023] proved empirically that sharing information and integrating customers represent significant determinants of SC performance.

Furthermore, the study outcomes confirmed the significant influences of goal congruence on SC performance. Stated differently, when supply chain members align their objectives and recognize the importance of collaboration throughout the supply chain, this will lead to improved supply chain performance. A number of earlier studies confirmed that increased levels of joint participation by supply chain members in conducting joint activities within a collaborative spirit helps to achieve higher levels of supply chain performance [García-Alcaraz et al. 2021].

Consistent with previous empirical studies [Eriksson & Pesämaa 2007; Eyaa et al. 2010; Simatupang & Sridharan 2004], a positive and significant association was found between incentive alignment and SC performance. These results imply that enhancing performance requires that SC members perform incentive alignment practices through collaborative creation of mechanisms for mutual performance assessment and promotion, expense allocation and joint management of potential SC risks.

The study results confirmed the positive influence of collaborative communication on SC performance. To put it another way, improved SC performance relies on implementing collaborative communication between SC members through maintaining regular and frequent interactions, promoting informal communication, as well as employing a wide range of communication channels. These findings are consistent with past studies showing that collaborative communication constitutes a relevant determinant of relational performance metrics [Chen et al. 2013].

Moreover, the findings showed that joint knowledge creation has a significant impact upon supply chain performance. To be precise, joint knowledge creation among supply chain members refers to the shared exploration and acquisition of new and relevant knowledge, its integration and implementation, shared recognition of customer needs, the discovery of emerging markets, and the understanding of competitors' intentions and capabilities. This result is congruent with previous studies outlining that joint knowledge creation significantly influences collaborative advantage through enhancing innovation, quality and efficiency [Uca et al. 2018].

In contrast to earlier studies showing a positive influence of decision synchronisation [García-Alcaraz et al. 2021] on SC performance, the results of the current study demonstrated no significant association between these variables in the context of automotive SC. The above result supports the conclusions of Eyaa et al. [2010], confirming that decision synchronisation has no significant influence on SMEs' supply chain performance. Similarly, Wiengarten et al. [2010]

reported that decision synchronisation does not necessarily imply increased performance.

Finally, the findings revealed no significant association between resource sharing and SC performance. This is consistent with an earlier study that concluded that under high uncertainty, the link between resource sharing and performance becomes lower [Maghsoudi & Pazirandeh 2016].

CONCLUSIONS

The purpose of the current research was to explore empirically the effect of SC collaboration practices on automotive SC performance. More precisely, this study has attempted to check the link between different aspects of SC collaboration, including decision synchronization, collaborative communication, incentive alignment, goal congruence, information sharing joint knowledge creation, and resource sharing on SC performance. The findings highlight that information sharing, collaborative communication, goal congruence, joint knowledge creation, and incentive alignment provide a basis for enhancing the level of SC performance. These findings offer a certain number of implications for theory and practice.

The SC management literature has explored the link between SC collaboration and SC performance. It is generally confirmed that collaborative SC positively affects the level of SC performance, whereas the modalities of association between these constructs varied from one study to another. In other words, there is a considerable difference in the measurement scales used to operationalize these concepts depending upon who considers them as one-dimensional or those who mobilize them as multidimensional concepts. Therefore, the theoretical implication of this study is related to using a multifaceted measure of SC collaboration. In addition, this research brings additional empirical evidence of the positive impact of SC collaboration on SC performance.

This study suggests a novel approach that might help practitioners by identifying ways to reach and sustain a high-level of SC performance. The considerable influence of information sharing, incentive alignment, collaborative communication, goal congruence, and joint knowledge creation on SC performance should persuade SC managers to carefully consider these collaborative practices in order to meet clients' specific requirements quickly, as well as to react to changing client demands by rapidly adapting production capacity. In short, members of the Moroccan automotive supply chain are encouraged to:

- engage in a timely exchange of accurate, complete, and confidential information.
- agree on SC goals, the importance of collaboration, and opportunities for overall supply chain improvement.
- develop co-develop systems to know each other's performance (dashboard), to share costs and risks that may occur in the supply chain.
- have frequent contacts on a regular basis, making available many communication channels leading to discuss any SC decision-making.
- jointly seek and obtain relevant new knowledge, attempting to assimilate and apply it jointly.
- discover jointly clients' needs, emerging markets, and analyze competitors' intentions and capabilities.

Although these are valuable implications, this research contains certain limitations that may be addressed in future empirical investigations. This study was exploratory with a small sample size, which prevents the results from generalizability. The expansion of the existing dataset may be appropriate in order to generalize the study findings. This expansion could potentially facilitate more widely applicable and representative results. Finally, it will be relevant to extend the proposed model by including the firm's performance as the dependent variable.

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ORIGINAL PAPER

ADAPTIVE DECISION-MAKING STRATEGY FOR SUPPLY CHAIN SYSTEMS UNDER STOCHASTIC DISRUPTIONS

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ABSTRACT. Background: Supply chain management is becoming more complex and essential with the development of the economy and globalization. Due to several interrelated and integrated logistical components, today's global supply chains are typically nonlinear dynamical systems that may show unpredictable, chaotic, or counterintuitive behaviors. In a volatile business environment, a company must integrate a decision-making strategy to achieve its strategic goals. Digitizing any business can keep up with supply chains that have become increasingly global and complex.
Methods: Digital transformation has been rapidly adopted across supply chain networks. A three-echelon supply network has been formulated in discrete time domains for exploring the complex behavior of the dynamical system. The discrete-time models fit more naturally to describe supply chain activities. This paper presents the adaptive management strategy to control the dynamic supply chain systems under uncertainty. The adaptive law is implemented based on the gradient descent method so that it can readily update the control gains of the decision-making strategy. The efficient management strategy helps policymakers implement a decision-support system more precisely and timely.
Results: The paper aims to implement the PID controller with adaptation law in supply chain management's chaotic suppression and synchronization problems under stochastic events. Numerical simulations are presented to evaluate the validity of the proposed algorithms for the operations management of dynamic supply chain networks. The proposed adaptive control strategy provides superior performance and accuracy over classical control strategies. The decision-making algorithms ensuring business profitability are realized by an adaptive management strategy to cope with market disruptions.
Conclusions: Disruptions like customer demand and market conditions impact on the multi-echelon supply chain system. A novel adaptive management strategy is presented to regulate uncertain supply chain systems against market disruptions. The control policy effectively utilizes chaos suppression and synchronization schemes to manage complex supply chain networks. The proposed management solutions will help logistics providers prepare for the future and gain a competitive advantage guaranteeing business resilience and sustainability against a volatile market.

Keywords: Supply chain systems, stochastic process, business profitability, adaptive decision-making strategy

INTRODUCTION

From the present perspective, supply chain management is becoming more complex and essential with the development of the economy and globalization. Due to several interrelated and integrated logistical components, today's global supply chains are typically nonlinear dynamic systems that may show unpredictable, chaotic, or counterintuitive behaviors. A company must integrate a decision-making strategy to achieve its goals in a volatile business environment. Digitizing any business can keep up with supply chains that have become increasingly global and complex. Digital transformation has been rapidly adopted across supply chain networks. Controlling and managing the supply chain system is more necessary for digital transformation. The control theory can help assist in more effective decisions and improve operational performance. For more than a

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decade, many researchers have studied the issues of supply chain design, analysis, modeling, and planning with a nonlinear framework. Most works deal with supply chain systems with continuous-time models, and just a few papers analyzed supply chain systems with discrete-time models. These discrete-time models fit more naturally to describe supply chain activities. In supply chain systems, some imponderable factors might result in nonlinearity and chaotic activities (Kocamaz et al., 2016). The complexity of uncertainty has become the norm in real supply chains. The chaotic supply chain system is one of many supply chain systems becoming the subject of analysis and research. Although chaotic behavior is often considered an undesirable phenomenon, it can provide beneficial features to describe complex nonlinear dynamics of the systems. Chaotic behaviors in the supply chain networks are sometimes caused by sudden changes in demands, disrupted by transportation, weather, disasters, pandemics, and more uncertain factors. The global pandemic and wars have recently posed challenges to supply chains and worldwide logistics, triggering new research areas in supply chain resilience (Ivanov, 2022). To propose the mathematical model for complex supply chain systems, numerous studies have been done on various chaotic systems like Chua, Lorenz, Sprott, Jerk, Lu, etc. Lorenz studied chaos mathematically for the first time in 1963. The chaotic supply chain modeling with the bullwhip effect was introduced (Lei et al., 2006). A three-echelon supply chain with bifurcation analysis and synchronization problems has been described by Anne et al. (2009). Xu et al. (2021) introduced a system dynamics method to manage a chaotic supply chain based on adaptive sliding mode control. Cuong et al. (2021) analyzed a production–distribution model in the nonlinear supply chain system using the adaptive sliding mode controller. Many methods are proposed for modeling the supply chain systems. The system dynamics can be analyzed in continuous-time form (Anne et al., 2009; Ardakani et al., 2020; Cuong et al., 2021; Ghadimi & Aouam, 2021; Lei et al., 2006), while some researchers analyze the system in discrete-time form (Tempelmeier, 2006). In aspects of the relationship between productivity and distribution, some articles discuss a mixed-integer programming model for a multi-period, multi-product supply chain considering conflicting economic and social responsibility objectives (Ardakani et al., 2020); optimizing the production capacity and safety stocks in a serial production–distribution system providing multiple products under a guaranteed service approach (Ghadimi & Aouam, 2021); analyzing and managing production–distribution in a nonlinear supply chain model using sliding mode control theory (Cuong et al., 2021). A multi-echelon nonlinear framework, which can be transformed into the Lorenz equation as a chaotic demonstration, has been presented to describe the supply chains considering the production of the manufacturer, distributor storage, retailer transportation, safety stock, and customer satisfaction (Lei et al., 2006; Anne et al., 2009; Xu et al., 2021). Numerous chaotic cases exist in complex supply chain networks, and economic and business models. A small change can be amplified to have a large effect on the system with a highly sensitive dependence on initial conditions. Chaotic phenomena contribute to exploring short-term changes in demand as the disruptive behavior experienced within the supply chain networks. For the decision-making strategy on chaotic suppression and synchronization problems, the control theory might provide sufficient mathematical tools to analyze, design, and simulate the supply chain management systems based on a system dynamics approach (Sarimveis et al., 2008). The main goals of chaotic system control are to realize the closed-loop supply chain systems for removing chaotic behaviors and synchronizing sudden changes in market demands. Several control theories have been proposed in regulating chaotic systems: linear feedback control (Kocamaz & Uyaroğlu, 2014) was considered to regulate continuous time Rucklidge chaotic system; an adaptive sliding mode controller (Xu et al., 2021; Cuong et al., 2021) was realized in managing chaotic supply chains in a stochastic environment; intelligent control and synchronization of chaotic supply chains (Kocamaz et al., 2016) were implemented using adaptive neuro-fuzzy inference system; and robust controllers (Govindan & Cheng 2018; Gholami et al., 2019; Zhang & Cui, 2021) were proposed for dynamical systems, ensuring robustness against disturbances. Among the control theories, the PID controller is considered a robust control technique for nonlinear dynamical systems (Amir et al., 2020). This controller is still widely used because of its structural simplicity, reputation, robustness, and easy implementation. Its form is built based on the current tracking error, the sum of recent errors, and the derivative of the error. This paper aims to implement the PID controller with an adaptation law in the supply chain management's chaotic suppression and synchronization problems under stochastic events. An adaptation law will be designed based on errors between the actual system affected by disturbances and the system in ideal condition. The adaptation law can be integrated with other controllers such as sliding mode control (Chang & Yan, 2005); based on system error (Tsai et al., 2017; Zhang & Cui, 2021), and so on. The structure of this article has 5 sections. Section 2 introduces the supply chain system model with a local stability analysis. This is a discrete-time model using the Lorenz equation. The adaptive PID control synthesis with stability analysis is described in Section 3. Section 4 presents the results of numerical simulations to demonstrate the effectiveness of the designed control strategy. Finally, conclusions are made in Section 5.

MATHEMATICAL MODEL OF NONLINEAR SUPPLY CHAIN SYSTEMS

In this study, a multi-stage or multi-echelon supply chain system consists of multiple tiers, such as the manufacturer, the distributor, the retailer, and the customer. For dynamic modeling, an essential requirement is a clear understanding of the relationship among many elements in the supply chain systems. The dynamic model creates three typical processes: the manufacturer producing, the distributor handling, and the retailer shipping products to customers. The complex model incorporates different flows of activities, mechanisms, and functions. The generic supply chain model is shown in Fig. 1.

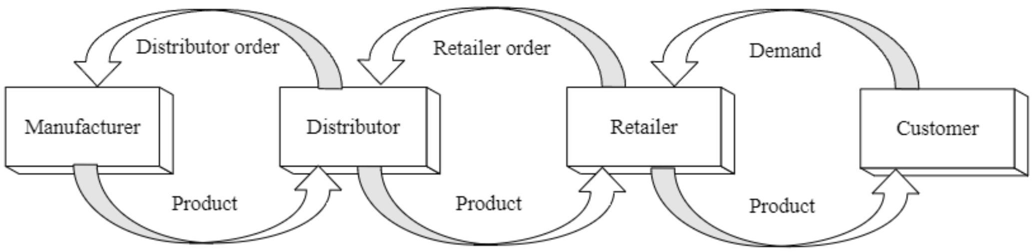


Fig. 1. Schematic diagram of the generic supply chain model.

Excellent supply chain management is crucial to profitability and maximizing customer satisfaction for any business. While typical management models are effectively described in a discrete-time domain, the supply chain dynamics are formulated and defined at each instance. It is noted that a fundamental variable is an inventory (or stock) in each echelon of the supply chain network. For the mathematical model, the following notations are used in this research (Lei et al., 2006):

i Time period.

x_i The quantity that the retailer of the products sends to the customer in the current period.

y_i The quantity that the distributor of the products handles in the current period.

z_i The quantity of products the manufacturer produces in the current period.

γ The delivery efficiency of the distributor.

σ The efficiency of the customer demand.

ε The efficiency of the retailer sending an order to the distributor.

θ The safety coefficient of the manufacturer.

d The stochastic disturbance.

u The control action in the decision-making.

In reality, the demand information transferred between each chain is delayed, leading to lead time in the supply chains. It means that the current order that the distributor received in the current period is the demand order of the retailer in the previous period. The quantity of the products that the retailer sends to the customer, x_i, depends on the number of products delivered from the distributor to the retailer and the number of satisfied customers in the previous period. This relation is given as follows:

$$x_i = \gamma y_{i-1} - \sigma x_{i-1} \quad (1)$$

The quantity of the products the distributor handles, y_i, is affected by the manufacturer's production and the retailer's order ($x_{i-1}z_{i-1}$). It also depends on the number of products the retailer sends to customers. The quantity of products the distributor sends to the retailer is given below:

$$y_i = \varepsilon x_{i-1} - x_{i-1}z_{i-1} \quad (2)$$

The last echelon in the system is the manufacturer, in which z_{i-1} denotes the number of products the manufacturer produces in the current period. To make a production decision exactly, the manufacturer has to get information from both the retailer and distributor ($x_{i-1}y_{i-1}$). In the real market, the manufacturer often makes more than demand, and it requires the safety coefficient based on the previous period (θz_{i-1}). The quantity of products the manufacturer produces is given below,

$$z_i = x_{i-1}.y_{i-1} + \theta z_{i-1} \quad (3)$$

where θ is the relative number, which is the supplier's capacity. This sometimes makes the quantity produced more or less than the previous period's demand or quite different from the demand they received from the market.

However, in reality, the supply chain system is affected by many stochastic factors. The real disturbances are introduced into the system as stochastic signals and added to the model, which can be used to describe actual market conditions. Then, the complete model is written as follows:

$$\begin{aligned} x_i &= \gamma y_{i-1} - \sigma x_{i-1} + d_{x_{i-1}} \\ y_i &= \varepsilon x_{i-1} - x_{i-1}z_{i-1} + d_{y_{i-1}} \\ z_i &= x_{i-1}.y_{i-1} + \theta z_{i-1} + d_{z_{i-1}} \end{aligned} \quad (4)$$

where the disturbances ($d_{x_{i-1}}$, $d_{y_{i-1}}$, and $d_{z_{i-1}}$) are given by the Wiener process or Brownian process and the widely used random or stochastic process. Brownian motion is frequently used to model supply chain systems and finance problems. It has been noted that stochastic behavior occurs in a deterministic manner in supply chain systems. The equilibrium analysis of the ideal system without disturbances is presented to explore the local behaviors of the nonlinear dynamical model. The specific parameters of the system are chosen as $(\gamma, \sigma, \varepsilon, \theta) = (10\,;5\,;15\,;-0.2)$ for numerical analysis. The three equilibrium points are determined by $E_1 = (0\,;0\,;0)$, $E_2 = (1.267\,;0.76\,;0.802)$ and $E_3 = (-1.267\,;-0.76\,;0.802)$. The Routh–Hurwitz criterion checks the local stability of near equilibrium points. Using the Jacobian matrix, the eigenvalues (λ_{E_i}) of equilibrium points (E_1, E_2, and E_3) are obtained as follows:

$$\begin{aligned} \lambda_{E_1} &= (-15\,;10\,;-0.2) \\ \lambda_{E_2} &= \lambda_{E_3} \\ &= (-14.6583\,;9.5351\,;-0.0768) \end{aligned} \quad (5)$$

where the eigenvalues identify unstable equilibria of a set of difference equations. As illustrated in Fig. 2, it is unstable if any eigenvalue at the equilibrium point has a positive real value. It is worth noting that this equilibrium analysis provides only the local stability of the ideal system.

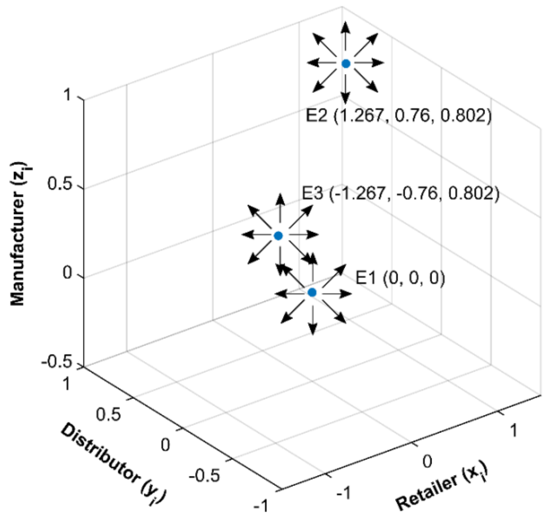
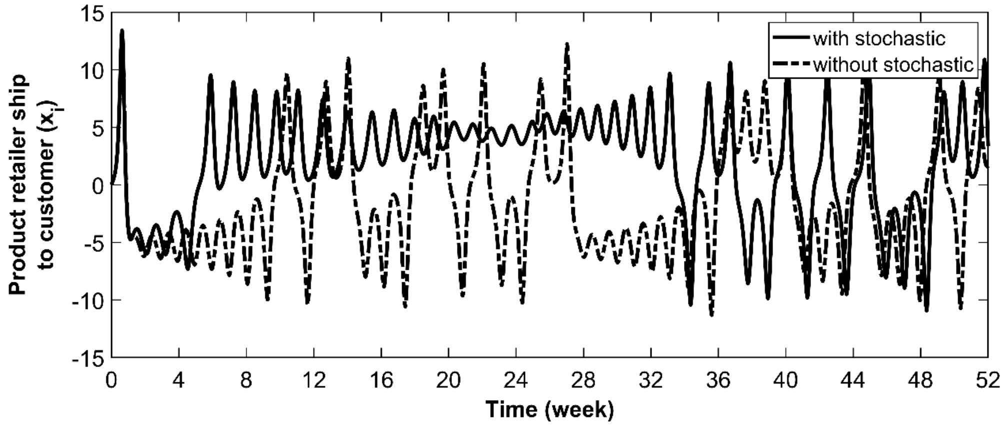
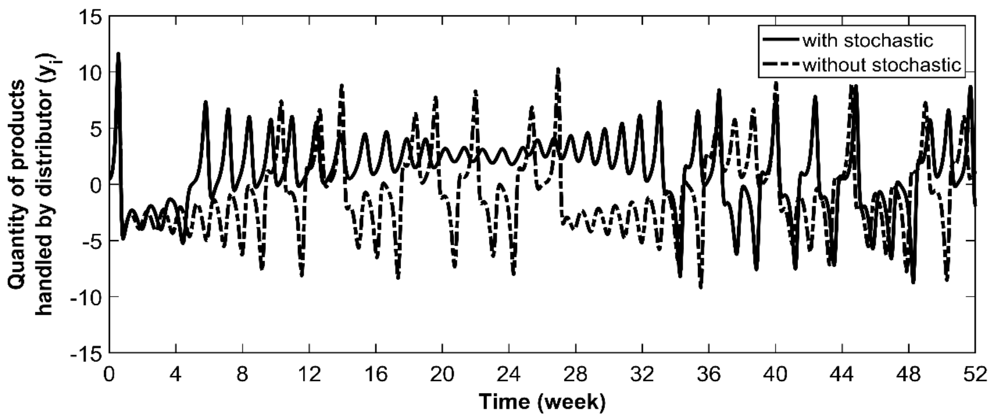


Fig. 2. Equilibrium analysis for the ideal system

Next, Fig. 3 shows the system response characteristics in the given periods (52 weeks of the stock level), including the ideal and uncertain systems with stochastic effects.



(a)



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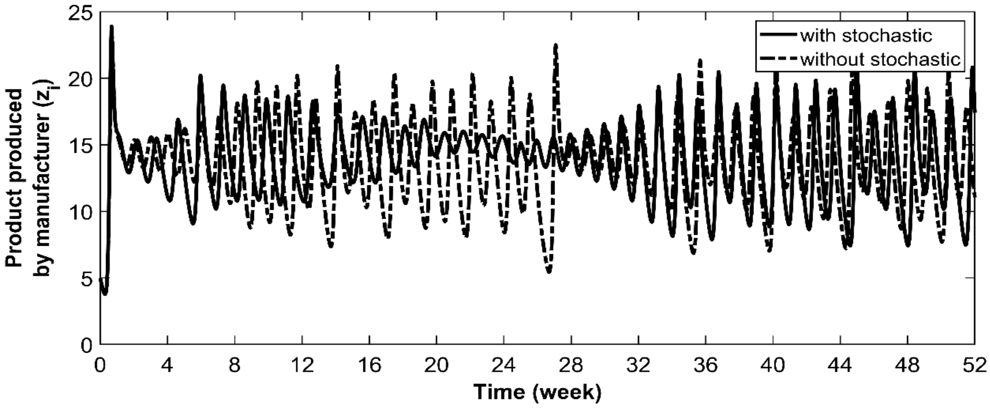


(c)

Fig. 3. Time responses of the supply chain system (in 52 weeks): (a) product retailer ships to the customer, (b) quantity of products handled by the distributor, and (c) product produced by the manufacturer.

DESIGN OF ADAPTIVE MANAGEMENT STRATEGY

The key objective in robust supply chain management is to satisfy customer demand while keeping optimal inventory (stock) levels in each echelon of the network against market disruptions. The robustness is related to the ability of the supply chains to resist changes under various (external or internal) disturbances. Building a robust management strategy gains more and more significance in the face of volatile markets. There is no single best way to realize an efficient supply chain strategy. In this study, a management strategy is designed based on the robust adaptive controller for making decisions quickly and efficiently. It is noted that efficient decision-making is essential for business success against disruptions. At each stage, the control input is the product in the system's transportation. For the closed-loop system design, a specific control input signal is introduced as u_i in the system (4). Then, the complete system is written in a compact form incorporating disturbance and control input as follows:

$$\begin{aligned} x_i &= \gamma y_{i-1} - \sigma x_{i-1} + d_{xi} + u_{xi} \\ y_i &= \varepsilon x_{i-1} - x_{i-1} z_{i-1} + d_{yi} + u_{yi} \\ z_i &= x_{i-1} y_{i-1} + \theta z_{i-1} + d_{zi} + u_{zi} \end{aligned} \quad (6)$$

As seen in Figs. 2 and 3, the chaotic attractor is observed when the system parameter values are chosen explicitly as follows: $(\gamma, \sigma, \varepsilon, \theta) = (10\,; 5;\ 15\,; -0.2)$, in which the external disturbances (d_{xi} , d_{yi} and d_{zi}) are described as stochastic processes. This model illustrates chaotic and complex dynamical behaviors within the framework of nonlinear dynamical systems (Xu et al., 2021). As mentioned, numerous chaotic phenomena exist in complex supply chain networks, illustrating sensitivity to initial conditions. Adaptive PID control with an adaptation law will be employed to change the dynamics of the supply chain model. As the controlled supply chain network becomes more extensive and complex, the supervisory controller will be additionally realized in the control system as the model-based strategy for discrete event models, which can be considered the boundary of the control system. Then the control input is given by a two-stage control mechanism,

$$u = \eta u_{pid} + \mu u_s \quad (7)$$

where η and μ are the effect factors of each control element; u_{pid} is the PID controller signal; u_s is the supervisory controller, which will be activated only when the state of the system exceeds some bounds and guarantees the stability of the system. Based on the gradient method, a proper adaptive law is designed to minimize the tracking error by updating control gains. Fig. 4 shows the general structure of the proposed adaptive control synthesis.

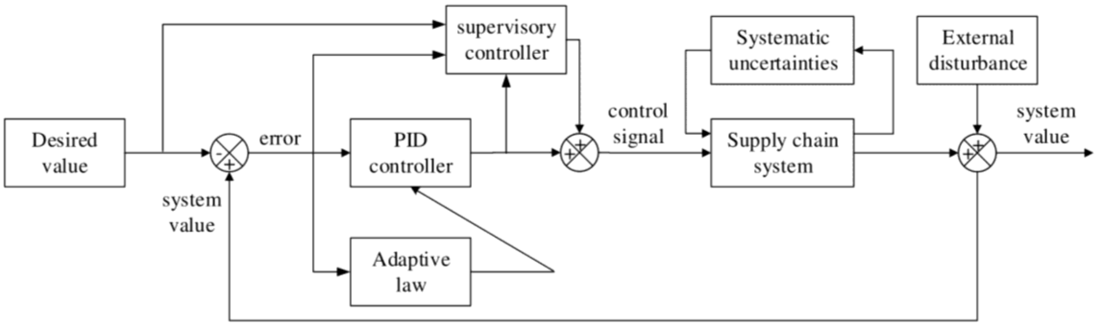


Fig. 4. Block diagram of the proposed adaptive control strategy

This two-state control scheme is intended to achieve better performance and strong robustness under stochastic events for making excellent and timely management decisions. In supply chain management, if the chaotic phenomena at stock levels across the stages cause unwanted problems, an active control scheme becomes necessary to eliminate undesirable dynamical behaviors. Furthermore, the synchronization scheme is essential for ensuring punctual optimal stock level, even if it has chaotic trajectories due to disruptions. Both scenarios are comprehensively discussed to guarantee a practical management strategy.

Dynamic suppression scheme

Since a classical PID controller is a reliable controller with a simple structure, it has been widely used in many applications for several decades (Parnianifard et al., 2020). The discrete form of the controller is generally given as follows:

$$u_{pid\_i} = K_p e_i + K_i \sum_{j=0}^{i} e_j + K_d(e_i - e_{i-1}) \tag{8}$$

The difference in the control signals taking data consecutively is given below:

$$\Delta u_i = u_i - u_{i-1} = K_p(e_i - e_{i-1}) + K_i e_i + K_d(e_i - 2e_{i-1} + e_{i-2}) \tag{9}$$

From Eqs. (8) and (9), the control signal u_{pid} is described by,

$$u_{pid\_i} = K_p(e_i - e_{i-1}) + K_i e_i + K_d(e_i - 2e_{i-1} + e_{i-2}) + u_{pid\_i-1} \tag{10}$$

where e_i , e_{i-1} , and e_{i-2} are the error signals, and K_p , K_i , and K_d specify the proportional, integral, and derivative gains, respectively. The vector of the tracking errors is defined as $e_i = [e_{xi}, e_{yi}, e_{zi}]^T$, and they can be given by

$$e_{xi} = x_r - x_i, e_{yi} = y_r - y_i, \text{ and } e_{zi} = z_r - z_i \tag{11}$$

where x_r , y_r , and z_r are the desired reference signals for the system. Eq. (6) is re-written in compact form using matrices and vectors:

$$w_i = Aw_i + f(w_i) + d_i + u_i \tag{12}$$

where $w_i = [x_i, y_i, z_i]^T$, $f(w_i) = [0, -x_i z_i, x_i y_i]^T$, $d_i = [d_{xi}, d_{yi}, d_{zi}]^T$ and $u_i = [u_{xi}, u_{yi}, u_{zi}]^T$.

Using the error vector, $e_i = w_r - w_i$, the control signal at each instance in the system is given by

$$u_{pid} = \begin{bmatrix} u_{pid\_x_i} \\ u_{pid\_y_i} \\ u_{pid\_z_i} \end{bmatrix} = \begin{bmatrix} K_{px}(e_{x_i} - e_{x_{i-1}}) + K_{ix}e_{x_i} + K_{dx}(e_{x_i} - 2e_{x_{i-1}} + e_{x_{i-2}}) + u_{pid\_x_{i-1}} \\ K_{py}(e_{y_i} - e_{y_{i-1}}) + K_{iy}e_{y_i} + K_{dy}(e_{y_i} - 2e_{y_{i-1}} + e_{y_{i-2}}) + u_{pid\_y_{i-1}} \\ K_{pz}(e_{z_i} - e_{z_{i-1}}) + K_{iz}e_{z_i} + K_{dz}(e_{z_i} - 2e_{z_{i-1}} + e_{z_{i-2}}) + u_{pid\_z_{i-1}} \end{bmatrix} \tag{13}$$

To derive the adaption laws for the control gains, the error function is defined below.

$$E_i = \frac{1}{2}e_i^T e_i = \frac{1}{2}(e_{xi}^2 + e_{yi}^2 + e_{zi}^2) \tag{14}$$

The parameters (K_p, K_i, and K_d) can be tuned by using the gradient descent method. The rules to update the controller parameters are

$$K_{Pj}(i+1) = K_{Pj}(i) + \Delta K_{Pj}(i) \tag{15}$$
$$K_{Ij}(i+1) = K_{Ij}(i) + \Delta K_{Ij}(i) \tag{16}$$
$$K_{Dj}(i+1) = K_{Dj}(i) + \Delta K_{Dj}(i) \tag{17}$$

where the subscript is specified by $j = \{x, y, z\}$. Using the chain rule, the following equations are obtained:

$$\Delta K_{Pj} = -\psi_{Pj}\frac{\partial E_i}{\partial K_{Pj}} = -\psi_{Pj}\frac{\partial E_i}{\partial e_{ji}}\frac{\partial e_{ji}}{\partial j_i}\frac{\partial j_i}{\partial u_{pid\_j}}\frac{\partial u_{pid\_j}}{\partial K_{Pj}} = \psi_{Pj}e_{ji}.(e_{ji} - e_{ji-1}) \tag{18}$$

$$\Delta K_{Ij} = -\psi_{Ij}\frac{\partial E_i}{\partial K_{Ij}} = -\psi_{Ij}\frac{\partial E_i}{\partial e_{ji}}\frac{\partial e_{ji}}{\partial j_i}\frac{\partial j_i}{\partial u_{pid\_j}}\frac{\partial u_{pid\_j}}{\partial K_{Ij}} = \psi_{Pj}e_{ji}^2 \tag{19}$$

$$\Delta K_{Dj} = -\psi_{Dj}\frac{\partial E_i}{\partial K_{Dj}} = -\psi_j\frac{\partial E_i}{\partial e_{ji}}\frac{\partial e_{ji}}{\partial j_i}\frac{\partial j_i}{\partial u_{pid\_j}}\frac{\partial u_{pid\_j}}{\partial K_{Dj}} = \psi_{Pj}e_{ji}.(e_{ji} - 2e_{ji-1} + e_{ji-2}) \tag{20}$$

where ψ_{Pj}, ψ_{Ij}, and ψ_{Dj} are the positive learning rates ($j = \{x, y, z\}$). Next, the model-based approach to supervisory control is realized as follows:

$$u_{si} = -Aw_i - f(w_i) - d_i + \delta_i \tag{21}$$

where $\delta_i = [\delta_{xi}, \delta_{yi}, \delta_{zi}]^T$ is the positive value set. Next, the closed-loop stability of the system will be analyzed using the Lyapunov theory.

Theorem 1: The system trajectories of the controlled supply chain system (6) converge to the set points in finite time if the controller is designed as Eq. (7) and adaptive law as Eqs. (15)–(17).

Proof: First, the Lyapunov energy function is considered as follows:

$$V_{2_i} = \frac{1}{2}e_i^T P e_i \tag{22}$$

where P is a positive definite symmetric matrix satisfying the Lyapunov equation:

$$A^T P + PA = -Q \tag{23}$$

and Q is also a positive definite symmetric matrix chosen by the system designer. The difference in function V_2 is defined by

$$\Delta V_{2_{i+1}} = V_{2_{i+1}} - V_{2_i} \tag{24}$$

The stable condition is defined as $\Delta V_2 \leq 0$. Eq. (24) is re-written as:

$$\begin{aligned}\Delta V_{2_{i+1}} &= \tfrac{1}{2}e_{i+1}^T P e_{i+1} - \tfrac{1}{2}e_i^T P e_i = \tfrac{1}{2}e_{i+1}^T P(w_{i+1} - w_i) - \tfrac{1}{2}e_i^T P e_i \\ &= \frac{1}{2}e_{i+1}^T P(Aw_i + f(w_i) + d_i + u_i - Aw_{i-1} - f(w_{i-1}) - d_{i-1} - u_{i-1}) - \frac{1}{2}e_i^T P e_i \\ &= -\frac{1}{2}e_{i+1}^T P\big[A(w_{i-1} - w_i) + \big(f(w_{i-1}) - f(w_i)\big) + (d_{i-1} - d_i) + (u_{i-1} - u_i)\big]\frac{1}{2}e_i^T P e_i \\ &= -\frac{1}{2}e_{i+1}^T P\big[A(w_{i-1} - w_i) + \big(f(w_{i-1}) - f(w_i)\big) + (d_{i-1} - d_i) + \eta u_{pid_i-1} + \mu u_{s_i-1} - \eta u_{pid_i} - \mu u_{s_i}\big] - \frac{1}{2}e_i^T P e_i \\ &= -\frac{1}{2}e_{i+1}^T P\big[A(w_{i-1} - w_i) + \big(f(w_{i-1}) - f(w_i)\big) + (d_{i-1} - d_i) + \eta u_{pid_i-1} \\ &\qquad + \mu(-Aw_{i-1} - f(w_{i-1}) - d_{i-1} - \delta_{i-1}) - \eta u_{pid_i} - \mu(-Aw_i - f(w_i) - d_i - \delta_i)\big] - \frac{1}{2}e_i^T P e_i \\ &= -\frac{1}{2}e_{i+1}^T P\big[\eta u_{pid_i-1} - \eta u_{pid_i} - \delta_{i-1} + \delta_i\big] - \frac{1}{2}e_i^T P e_i\end{aligned} \tag{25}$$

In the formula, some assumptions are made, such as $\delta_{i-1} \le \eta u_{pid(i-1)}$ and $\delta_i \ge \eta u_{pid(i)}$, so that $\Delta V_2(e_i) \le 0$ is ensured for the closed-loop stability. The proof is completed. ■

By employing Theorem 1, the proposed control strategy realizes the suppression scheme.

Synchronization scheme

The previous section shows how to design an adaptive management strategy to suppress deterministic chaos. With a synchronization strategy, the business enterprises would produce the exact number of goods necessary to meet actual demand in real-time. It uses a control input to force the system toward the desired value. In this scheme, it is essential to define the ideal reference model of a nonlinear master and slave chaotic system. The control input will drive the chaotic system (slave), affected by disturbances, to follow the ideal supply chain dynamics (master). The ideal reference system equation (master) is given by

$$\begin{aligned} x'_{ri} &= \gamma y'_{ri-1} - \sigma x'_{ri-1} \\ y'_{ri} &= \varepsilon x'_{ri-1} - x'_{ri-1} z'_{ri-1} \\ z'_{ri} &= x'_{ri-1} . y'_{ri-1} + \theta z'_{ri-1} \end{aligned} \tag{26}$$

From Eq. (6), the actual system (slave) with the disturbances and the controller is given by

$$\begin{aligned} x'_i &= \gamma y'_{i-1} - \sigma x'_{i-1} + d'_{xi} + u'_{xi} \\ y'_i &= \varepsilon x'_{i-1} - x'_{i-1} z'_{i-1} + d'_{yi} + u'_{yi} \\ z'_i &= x'_{i-1} . y'_{i-1} + \theta z'_{i-1} + d'_{zi} + u'_{zi} \end{aligned} \tag{27}$$

This formulation deals with the synchronization strategy of two identical supply chains with different initial conditions. By setting $w'_i = [x'_i, y'_i, z'_i]^T$ and $w'_{ri} = [x'_{ri}, y'_{ri}, z'_{ri}]^T$, the error vector of the synchronized two systems is written as follows:

$$e'_i = w'_i - w'_{ri} \tag{28}$$

Based on the control synthesis described before, the proposed control algorithm is designed by

$$u'_i = u'_{pid(i)} + u'_{s(i)} \tag{29}$$

Similarly, the PID controller and supervisory controller are given by

$$\begin{aligned} u'_{pid(i)} &= K'_{p(i)} . (e'_i - e'_{i-1}) + K'_{i(i)} e'_i \\ &\quad + K'_{d(i)} . (e'_i - 2e'_{i-1} + e'_{i-2}) \end{aligned}$$

$$u'_{s(i)} = -A'w'_i - f'^{(w_i)} - d'_i + \delta'_i$$

Theorem 2: The synchronizing trajectories of the supply chain systems in Eqs. (26)-(27) with an unknown parameter for any initial conditions will be asymptotically stable by employing the adaptive control law described in Eq. (29).

Proof: Since the proof is similar to that of Theorem 1, the detailed proof is omitted for brevity.■

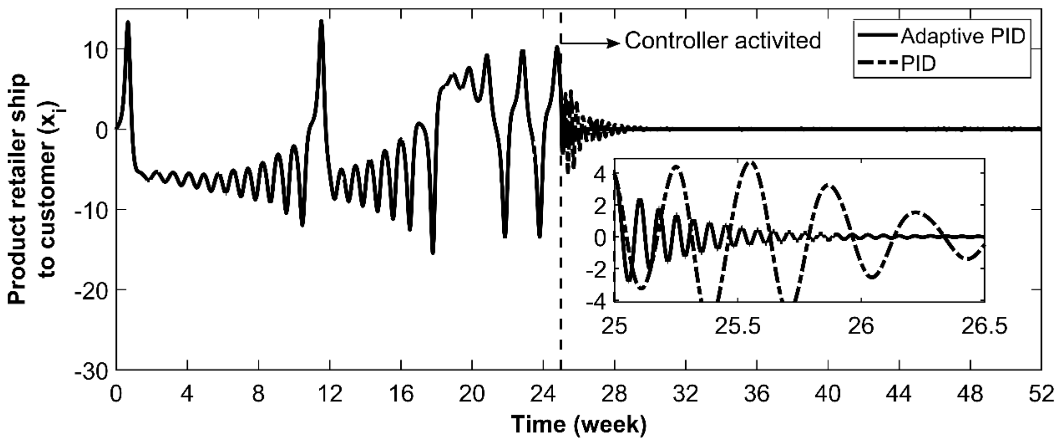
Likewise, by utilizing Theorem 2, the synchronization error signals are asymptotically zero, $\left\|e_i^{'}\right\|_2 = 0$ or $w_i' \to w_{ri}'$ asymptotically. Then the master-slave synchronization scheme is realized by the proposed control strategy.

NUMERICAL SIMULATIONS

In this section, numerical simulations will be carried out to verify the management strategy's performance when applied to the supply chain control system. The decision-makers want to keep the optimal stock level susceptible to oscillations in demand and inventory level as orders pass through the supply chain networks under uncertainty. Sometimes, effective short-term decision-making processes are essential for guaranteeing business sustainability through resilience. Chaotic phenomena contribute to short-term changes in demand as disruptive behavior is experienced within the supply chain networks. Several controllers can be implemented to explore their effects on efficiency and performance for timely and efficient policy making. Two chaotic scenarios are thoroughly discussed to guarantee a practical management strategy.

Chaos suppression policy

First, removing chaos is the key to managing uncertain supply chain networks as a risk management strategy against volatility. The initial control gains are selected as follows: $(K_{px}, K_{ix}, K_{dx}) = (1.5, 0.85, 0.5)$; $(K_{py}, K_{iy}, K_{dy}) = (2, 0.2, 1.5)$; $(K_{pz}, K_{iz}, K_{dz}) = (2.5, 0.3, 2)$; and $(x_r, y_r, z_r) = (0, 0.5, 5)$. For comparison purposes, the system performance with the classical PID controller is shown in Figs. 5~7, where the control parameters are chosen as follows: $(K_{px\_r}, K_{ix\_r}, K_{dx\_r}) = (1, 0.75, 0.5)$; $(K_{py\_r}, K_{iy\_r}, K_{dy\_r}) = (1.5, 0.2, 1)$; and $(K_{pz\_r}, K_{iz\_r}, K_{dz\_r}) = (2, 0.3, 0.75)$. The control performances on the time response, the tracking error, and the control activity are illustrated in Figs. 5, 6, and 7, respectively. The control action starts on the 25th week over 52 weeks. The simulation results show that the proposed adaptive control strategy provides superior performance and accuracy over classical control law. Notably, the control activity (or energy expenditure) required for the adaptive control approach is smaller than the control system with a classical controller. The activity signals are closely related to the control energy and time spent on decision-making. The strategic business policy is a standing plan that provides guidelines for timely and efficient decision-making. Based on the proposed approach, the policymaker can fully control the supply chain systems with less decision-making action.



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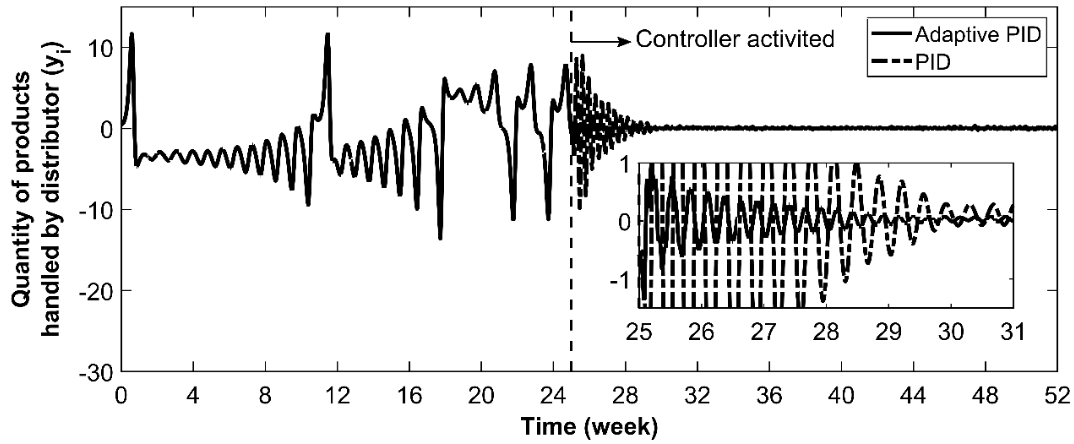

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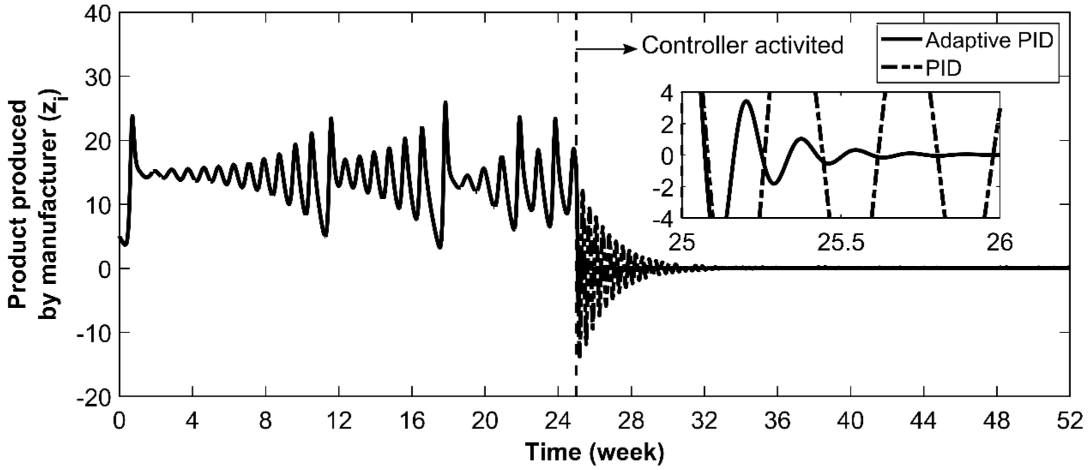
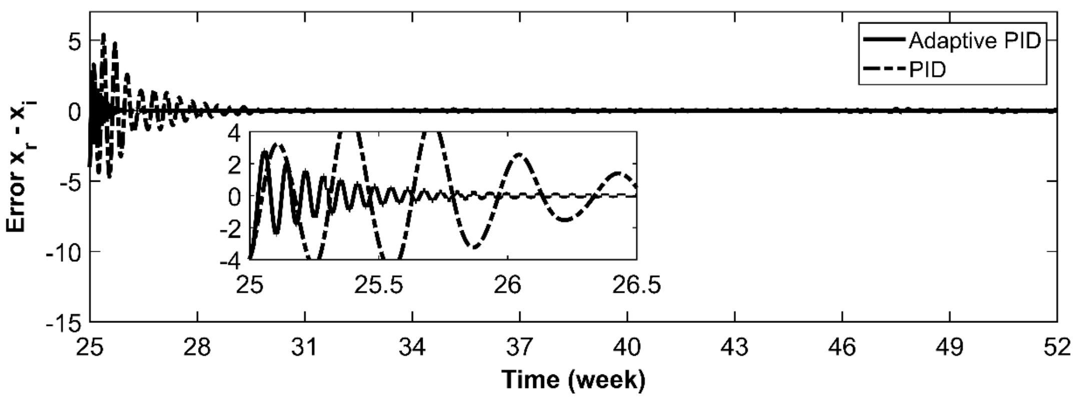
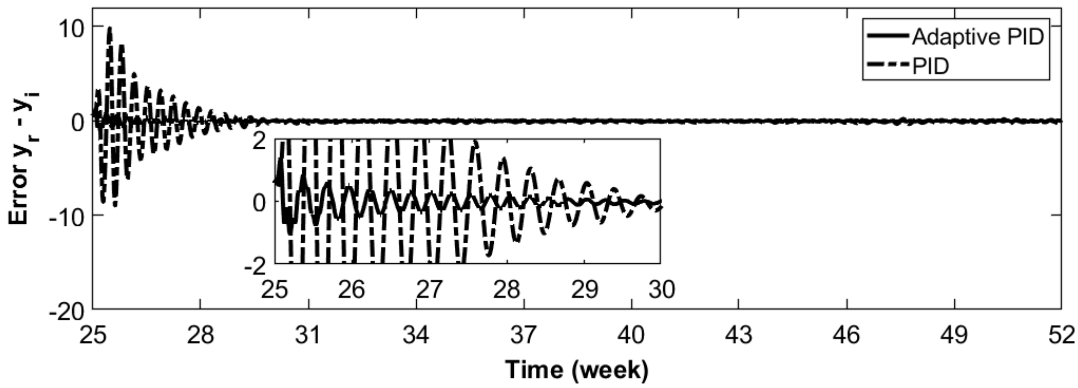


(c)

Fig. 5. Time responses of the system with control action at the 25th week: (a) product retailer ships to the customer, (b) quantity of products handled by the distributor, and (c) product produced by the manufacturer.



(a)



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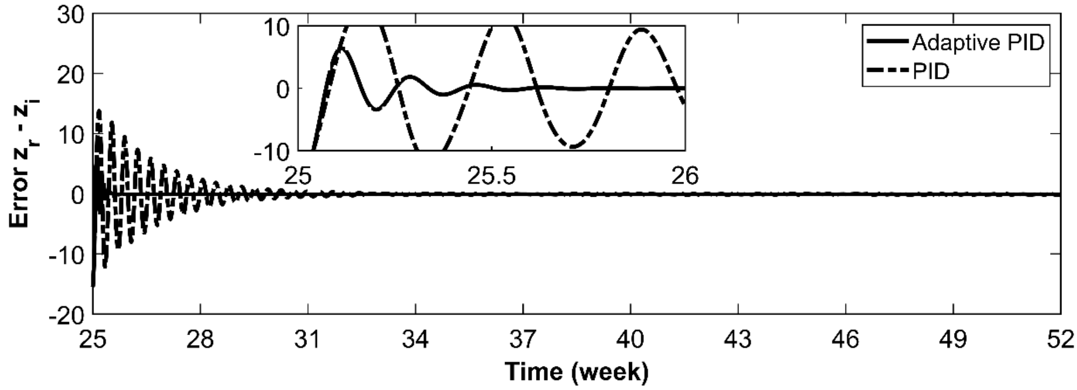
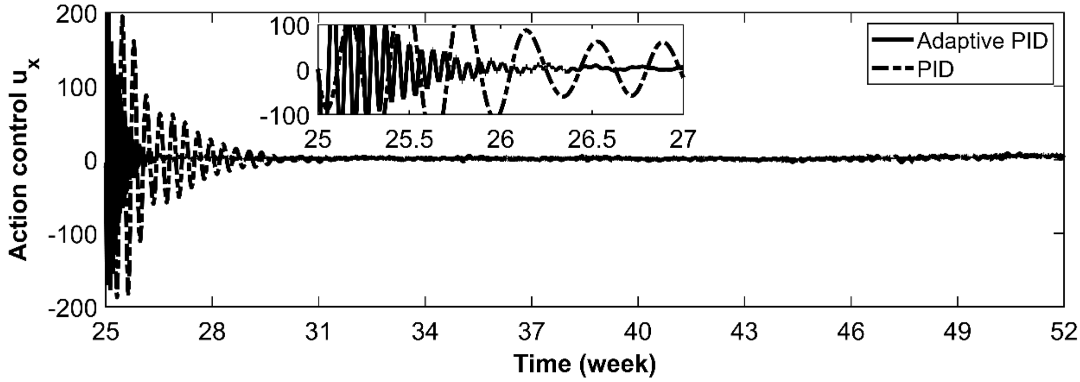
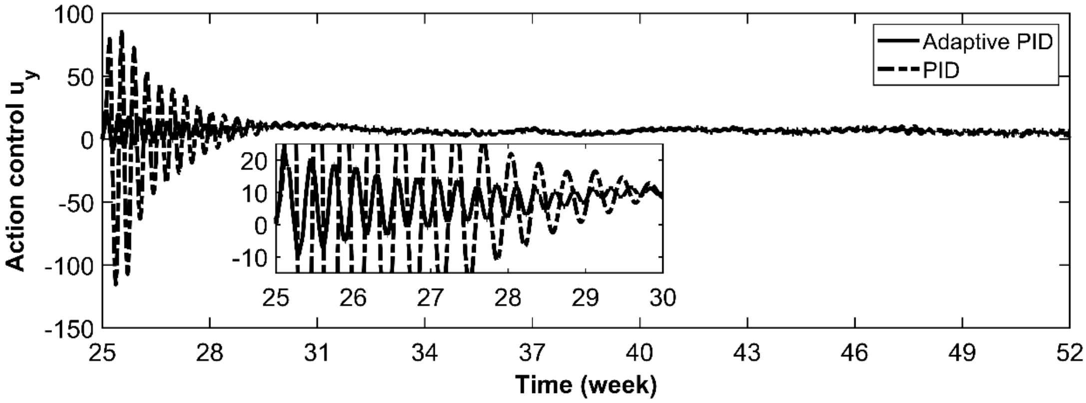


(c)

Fig. 6. Tracking performances of the system with control action at the 25th week: (a) tracking error of the retailer, (b) tracking error of the distributor, and (c) tracking error of the manufacturer.



(a)



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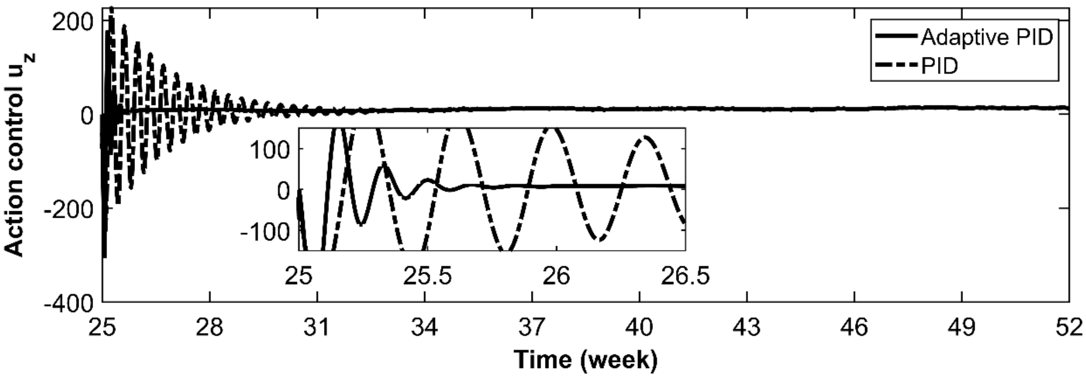
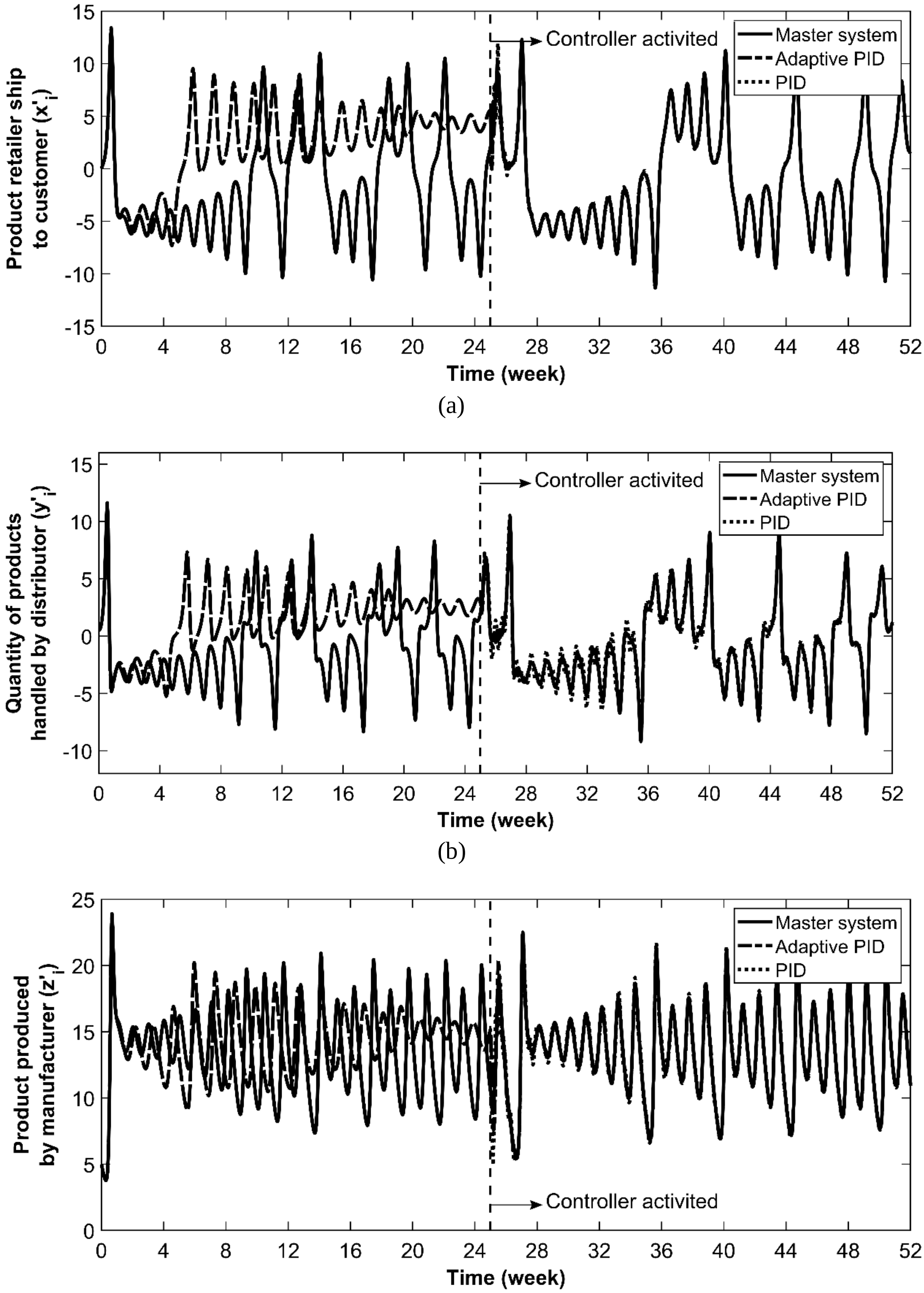


(c)

Fig. 7. Control activity signals (or energy expenditure) of the control laws for suppression policy: (a) control action at the retailer, (b) control action at the distributor, and (c) control action at the manufacturer.

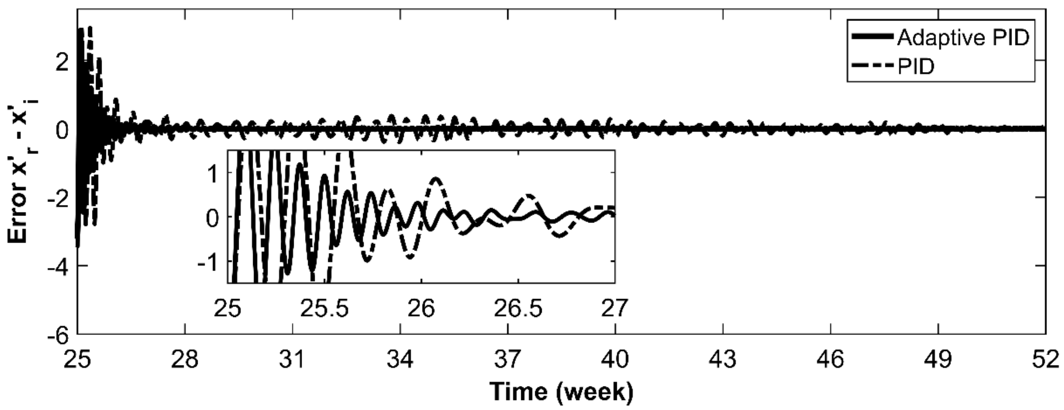
Chaos synchronization policy

The synchronization scheme requires the supply chain system, where information or data should be collected, analyzed, and utilized in real-time to guarantee constant visibility. For short-term periods, sudden changes, such as chaotic surges in demand, can occur unexpectedly in the supply chain networks. Then, the synchronization strategy can help policymakers keep informed about the company's internal stock level with the current picture at the various stages to ensure increased sales and profits with less control action. For this scenario, the controller's initial gains are chosen as follows: $(K_{px}, K_{ix}, K_{dx}) = (1{,}0.9{,}0.75)$; $(K_{py}, K_{iy}, K_{dy}) = (1.5{,}0.35{,}1.5)$ and $(K_{pz}, K_{iz}, K_{dz}) = (2{,}0.15{,}0.5)$. The classical PID controller's initial gains are chosen as follows: $(K_{px\_r}, K_{ix\_r}, K_{dx\_r}) = (1{,}0.75{,}0.5)$; $(K_{py\_r}, K_{iy\_r}, K_{dy\_r}) = (1.5{,}0.2{,}1)$ and $(K_{pz\_r}, K_{iz\_r}, K_{dz\_r}) = (2{,}0.3{,}0.75)$. Other parameters of the system have the same values of being used in chaos suppression: $(\gamma, \sigma, \varepsilon, \theta) = (10\,;5\,;1\,5\,;-0.2)$. The controller is activated at the 25th week over 52 weeks for all simulations. The synchronization scheme is intended to drive the slave system to follow the ideal system in the disturbance. Fig. 9 shows the errors between the slave system and the master system. As depicted in the simulation results (Figs. 8-10), the proposed adaptive control strategy provides superior performance and accuracy over the classical control strategy. Policymakers need to make decisions quickly and efficiently in a rapidly changing world. From this synchronization approach, making good and timely management decisions can make your business more successful by ensuring competitive advantage by growing revenue and increasing your customer in a volatile market environment.



(c)

Fig. 8. Time responses of state variables for supply chain synchronization with control input at the 25th week: (a) product retailer shipping to the customer, (b) quantity of products handled by the distributor, and (c) product produced by the manufacturer.



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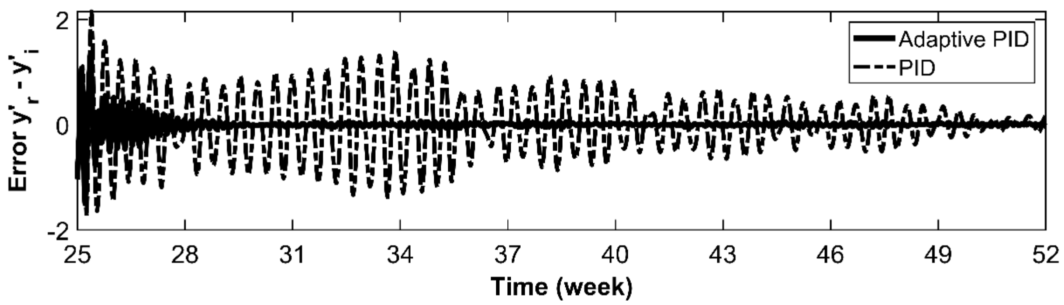

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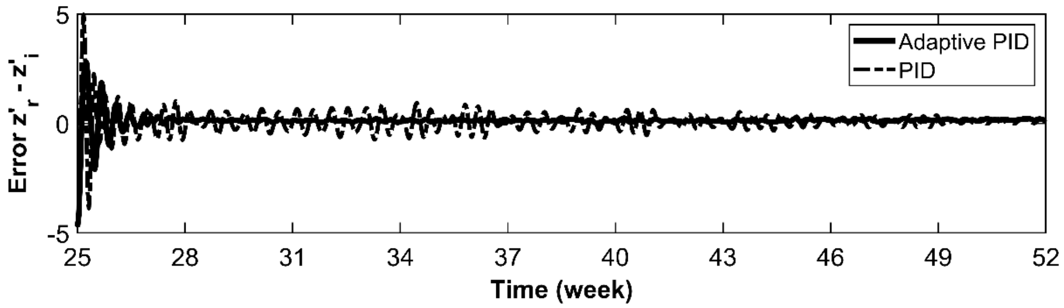

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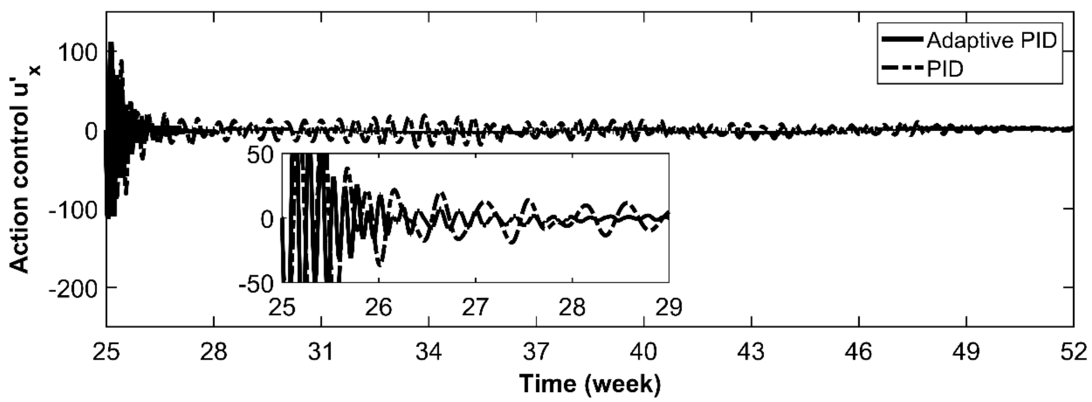
Fig. 9. Time responses of tracking errors for supply chain synchronization with control action at the 25th week: (a) tracking error of the retailer, (b) tracking error of the distributor, and (c) tracking error of the manufacturer.



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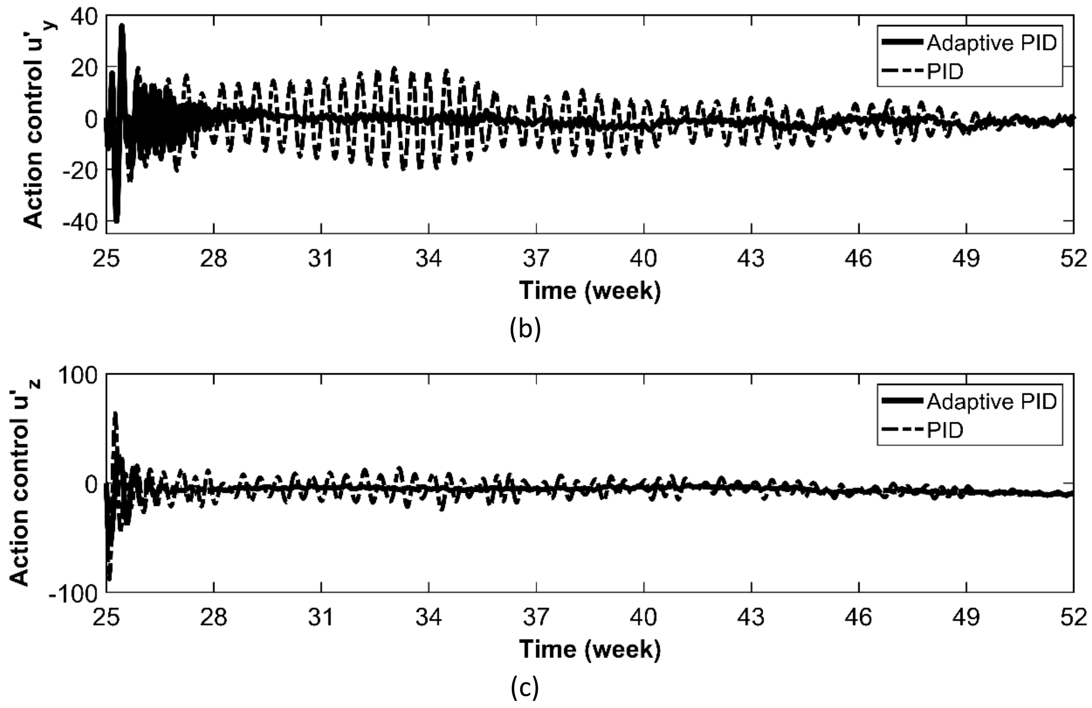

Fig. 10. Control activity (or energy expenditure) of control laws for synchronization policy: (a) control action at the retailer, (b) control action at the distributor, and (c) control action at the manufacturer.

DISCUSSION AND CONCLUSION

This paper proposes a novel adaptive management strategy to regulate uncertain supply chain systems against market disruptions. First, a multiple-echelon system is built with the framework of nonlinear dynamics in a discrete event under stochastic disturbances. The chaotic system describes the complex relationship and dynamic integration between the critical supply chain elements for short-term processes. In reality, the market is always affected by uncertain disrupting factors, which cause stochastic effects on the system. The efficient management strategy helps policymakers implement a decision-support system in a more precise and timely way. A new PID-based adaptive controller has been proposed to realize the chaos suppression and synchronization strategy. The adaptive law is designed based on the gradient descent method so that it can readily update the control gains of the decision-making strategy. Extensive numerical simulations are performed to verify the proposed control strategy. As illustrated in the various test scenarios, the proposed adaptive control strategy provides superior performance and accuracy over the classical control strategy. Cuong et al. (2021) presented adaptive fractional-order sliding mode control synthesis for solving production-distribution problems in supply chain management. Xu et al. (2020) proposed adaptive sliding mode control for chaos suppression and synchronization in supply chain systems. Amir et al. (2020) proposed a computational method to find optimal PID controller gains. This article presents an adaptive PID algorithm for decision-making policy, in which control gains are updated based on tracking errors in supply chain behaviors. The proposed algorithm is easy to understand and implement, as it employs simple concepts such as tracking errors and adaptive mechanisms to deal with chaotic supply systems against disruptions. Based on the system dynamics and control theory, this study contributes to analyzing, integrating, and controlling the digitized management systems with chaotic behaviors in many of today's supply chains. Finally, the proposed management solutions will help logistics providers prepare for the future and gain a competitive advantage, guaranteeing business profitability against a volatile market.

ACKNOWLEDGMENTS

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Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All data generated or analyzed during this study are included in this article (and its supplementary information files).

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ORIGINAL PAPER

CIRCULAR SUPPLY CHAIN MANAGEMENT WITH BLOCKCHAIN INTEGRATION

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ABSTRACT. Background: Circular supply chain management encourages manufacturers to take advantage of used materials and industrial wastes, ensuring social and economic benefits of enhanced environmental sustainability in production. With the development of digital technologies, transactions can be recorded within distributed or decentralized ledger technology. To improve the reliability of digital transactions on the internet, manufacturers need to apply security software such as blockchain technology across a network. Blockchain technology in the supply chains brings transparency, traceability, and security to online transactions, increasing customer attractiveness to the used product and recycling process. Secure transactions might bring significant benefits to the future of the retail industry. The manufacturer exploits the retailer as an online store. Consumers access an online store for purchase, return, and comment on the manufacturer's products.

Methods: This research presents a novel meta-heuristic algorithm, specifically, adaptive particle swarm optimization (adaptive PSO), to determine the optimal policy for product price and quantity of materials imported from suppliers for maximizing total profits with sustainability. The adaptive PSO algorithm evaluates the fitness function involving discrete random variables. The supply chain model captures realistic conditions by considering the inherent uncertainties of customer demand. Two scenarios in business settings have been tested on the same customer demand. The proposed framework is intended to yield a more sustainable, resilient, and regenerative system, securing the data of the shared community.

Results: The swarm intelligence algorithm implements profit optimization to determine the unit price of the product and the number of materials to be imported. The numerical experiments are conducted to demonstrate the efficacy of the optimal strategy and to evaluate the effect of the number of used products returned to the recycling center. An effective circular supply chain management is realized based on a secure database shared across a network of participants. Key findings significantly contribute to the intelligent decision support system for optimizing inventory management under various stochastic scenarios.

Conclusions: Sharing, reusing, repairing, and remanufacturing help companies transition to a circular economy, minimize waste, diversify sources of supply, and maintain production continuity. Transactions on the blockchain framework become transparent and traceable. Based on the circular economy and blockchain platform, this study deals with an adaptive particle swarm optimization algorithm (APSO) to determine the optimal policy for product unit price and quantity of materials imported from suppliers to maximize total profits. The presented methodology can provide better supply chain visibility and traceability under highly realistic stochastic environments.

Keywords: Supply chain management, circular economy, blockchain technology, inventory management, particle swarm optimization

INTRODUCTION

Supply chain management has long been an important business activity in controlling the source of raw materials, the production rate, the inventory level, and the unit price of products. One of the ways to optimize profits is to manage consumer demand, which is typically unpredictable or volatile in a fluctuating market. Lin et al. [2021] evaluated the optimal number of buyers based on the Markov chain demand. In

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addition, adjusting product prices can also significantly impact profits. Kumar Jena et al. [2023] presented the pricing decision for optimizing competitive, sustainable processes in the digital supply chain. Asghari et al. [2022] proposed a closed-loop supply chain based on the pricing strategy. There is a growing awareness of environmental care in supply chains. The circular supply chain system is a dynamic model in a transition towards a sustainable economy, ensuring a more restorative and regenerative economy. This will help the supply chains to leverage the used materials to improve resource efficiency. The issues of growing importance include improving resource productivity, reducing waste, and maintaining sustainable practices. In supply chain management, environmental issues typically occur along with the production cycle, manufacturing practices, raw material handling, waste treatment, etc.

Scarcity and supplies of resources are now becoming the industry's biggest problem, especially after the COVID-19 pandemic and wars. Transportation delays have become more common due to centralized bans or blockade policies imposed by nations. To avoid interruptions in the production line, manufacturers must diversify sources of raw materials and methods of trading products. One of the ways to give manufacturers an additional source of raw materials and attract more customers is to adopt a recycling policy to collect used products or materials from customers and recycle them into usable raw materials. Waste can be transformed into high-quality secondary raw materials for making new products. The continual reuse of recycled materials in manufacturing is a part of the circular economy and is considered a vital strategy for supply chain innovation. Ghoushchi et al. [2021] proposed optimizing a multi-stage-multi-product closed-loop supply chain (CLSC) from a circular economy perspective. Sarkar et al. [2022] presented the nullification of food waste produced in the circular economy-driven two-stage supply chain model. The utilization of used products is the foundation for sustainable development. Between 2010 and 2020, approximately 131 articles were published on inventory management in the context of supply chain sustainability [Salas-Navarro et al. 2022]. With future trends in the shipping industry and the popularity of e-commerce platforms, customers can buy products online without visiting a physical store. Customers can easily search for products and check reviews or distribution information online. Digital online shopping boomed during the COVID-19 crisis. Maritime transport has played an essential role in response to the coronavirus pandemic and significantly contributed to world economic growth. Import and export ports worldwide are gradually developing in the direction of automation and port digitalization through IoT systems and management software. However, cyber-attacks are more widespread than ever before. An online transaction always comes with fraud risks due to inherent security susceptibility. Some malicious actors might steal transaction information.

Blockchain technology can help participants protect digital information from unauthorized access to ensure efficient supply chain management. This technique allows secure data transmission, based on a highly complex encryption system, which is similar to a company's accounting ledger, where banking information is closely monitored and recorded in all transactions on the peer-to-peer network. Blockchain technology is based on two main components: block and chain. The block is the place where data is entered into the system. The chain is a link that connects data blocks and has two heads. One is associated with a previous block by one hash code, and the other fuses with a current block by the same hash code. Data stored on the blockchain is digitally distributed to every node linked in the system, and the blockchain also works on the decentralized consensus mechanism. The shared information makes the data in the blockchain impossible to alter because it is also recorded in many different databases. When a database changes, the system will compare it with other databases to detect that change. With the emergence of cryptocurrencies, blockchain technology has been applied to many fields. Chinnaraj and Antonidoss [2022] proposed a methodology to develop intelligent secured inventory management, using blockchain technology. The applications and challenges of using blockchain technology in the maritime supply chain are presented by Liu et al. [2021]. In the circular economy-driven supply chain management by Ma and Hu [2022], the blockchain platform can solve some bottleneck problems that strictly affect the recycling of waste products. In addition to security issues, blockchain can impact the operating costs of a specific sector. Ho and Hsu [2020] analyzed the importance of critical factors in shipping companies with the effect of blockchain technology. These factors can impact the costs and level of risks. Park and Li [2021] proved that blockchain technology might bring supply chain sustainability.

This article employs blockchain technology to ensure supply chain transparency and traceability through a digitally distributed ledger. A new platform can potentially increase the customer's interest in products. In addition, the information in the blockchain supply chain, such as the shipping processes, the origin of raw materials, how to handle used products, customer contributions when returning used products, and manufacturer's policies, are shared with customers when customers make a purchase or return products that are no longer needed after use to the manufacturer. The customer will receive a discount voucher for each returned used product for the next purchase. Some scholars also mentioned the relationship between incentives and used product returns in the logistics and supply chain management (SCM) research field. Asghari et al. [2014] studied the relationship between incentive and product return in the reverse logistics network. Aras and Aksen [2008] proposed a nonlinear mixed-integer programming model for optimizing the facility allocation problem and the inventive values for each type of product return. However, previous studies only dealt with the relationship between incentives and product re-turns without considering factors such as recycling used products or the effect of the number of materials or products imported from outside.

The measure of profit the manufacturer can achieve comes from the difference between revenue and incurred costs. The economic Order Quantity (EOQ) model assesses supply chain costs through the number of raw materials imported from the supplier and the amount of inventory held by the manufacturer. Typical costs in the EOQ model are carrying (holding) costs and ordering costs. It is a measurement used in operations, logistics, and supply management. However, this paper will consider an additional recycling cost to represent the waste from recycling used products in the circular economy framework. Ouyang et al. [2005] used the EOQ model to evaluate the costs in the deteriorating inventory model under trade credits. Li et al. [2015] combined the Hamilton-Jacobi-Bellman equation and the EOQ cost policy to optimize the profit in the stochastic inventory model.

This paper does not consider a specific product but focuses on building a circular supply chain model for generic items under the influence of blockchain technology. Online stores could replace retailers, and at the same time, every transaction would be made within a blockchain framework. From information stored and shared by blockchain technology, customers can trace the origin of raw materials, production lines, discount information, and the purpose of recycling used products.

This paper aims to realize the optimal strategy for product price and the number of raw materials ordered from the supplier in the circular economy and the blockchain framework. The methodology used in this paper is the particle swarm optimization algorithm (PSO), a popular meta-heuristic strategy used for higher-level optimization problems. This swarm intelligence is applied to determine the optimal reorder point of a stochastic supply chain [2013]. The algorithm is also employed to optimize inventory total costs [2020]. Sometimes, this algorithm might get stuck at the local optimal point and take time to converge at the global optimal point. The adaptive PSO algorithm is an advanced version with adjusting parameters to achieve better optimal results and faster convergence. Zhan et al. [2009] introduced the APSO algorithm, adjusting inertia weights and control strategy for the acceleration coefficients to improve search efficiency. Most businesses are keen to put the theories into practice using the circular economy and blockchain framework. In this study, the novel decision-making strategy can offer new insights into effectively managing digital supply chain networks against market volatility. The key contributions of this paper are described as follows:

- Based on transaction information shared through blockchain technology, this work considers the customer demand or the raw material price affected by activities in the supply chains.

- The inventory model considers economic factors of production and consumption for eliminating waste and pollution, circulating products and materials, and regenerating nature.
- Circular supply chain dynamics are formulated under decentralized ledger technology.
- The swarm intelligence algorithm implements profit optimization to determine the unit price of the product and the number of materials to be imported.
- Numerical experiments are presented to validate the circular supply chain management, considering changes in the number of used products returned to the recycling center.

More importantly, the presented algorithms are robust and effective, linking a firm's *supply chain* strategy to its overall business strategy in a volatile market.

This paper is organized as follows. Section 2 discusses a literature review of relevant studies. Section 3 presents the circular supply chain model from a blockchain perspective. Section 4 introduces the APSO algorithm to find the optimal unit price and the number of materials needed to order from the supplier to maximize the total profit. Section 5 shows the numerical experiment to demonstrate the efficiency of the proposed approach. Section 6 presents the discussion with managerial insights. Finally, the conclusion is given in Section 7.

LITERATURE REVIEW OF RELEVANT RESEARCH

The circular supply chain system is a dynamic model that uses excess materials, waste, and used products as raw materials in production processes [Ghoushchi et al. 2021; Sarkar et al. 2022]. In the context of raw materials or resources becoming increasingly scarce and more expensive, the transition to circularity in the supply chain is essential, benefiting from high material and component recovery rates. It saves the environment and helps the company save money, providing a source of raw materials for production. Especially after the COVID-19 pandemic and recent wars, many enterprises are focused on a circular economy or sharing economy. During the pandemic, some countries issued blockade orders, the global supply chain became stagnant, and some factories couldn't get raw materials or workers for production. Atabaki et al. [2020] presented an optimal approach for a circular supply chain considering the costs associated with emissions, energy, and recovery facilities. Suhandi and Chen [2023] studied inventory optimization problems in the circular supply chain for the pharmaceutical market.

Along with the importance of the circular economy, digital technology is constantly evolving. Online payments via the internet have become popular along with decentralized and distributed databases—typically blockchain technology. The application of blockchain can bring many incredible benefits to supply chain networks, such as security, transparency, and traceability in digital transactions [Liu et al. 2021; Park and Li 2021]. Blockchain technology can further improve supply chain sustainability [Park and Li 2021]. Saurabh and Dey [2021] studied blockchain technology in the wine supply chain, such as implementing costs and ensuring product reliability and traceability. Blockchain technology is integrated into an e-commerce business, advancing digital transformation [Ma and Hu 2022]. Pakseresht et al. [2022] specified four significant areas of applying blockchain technology to the circular food supply chain system. Giovanni [2022] analyzed the critical benefits of blockchain technology in application to the circular supply chain model.

There are many ways to optimize supply chain networks. Manufacturers can use the Internet of Things (IoTs) and high-tech devices to optimize the supply chain [Saurabh and Dey 2021]. Govindan et al. [2023] analyzed routes for circular economy supply chains under the constraints of carbon tax policy. In addition, manufacturers can proactively consider effective inventory management to establish the desired profit [Asghari et al. 2022; Sarkar et al. 2022]. The firm's goal is to maximize profits by minimizing costs in inventory management. The EOQ model is commonly used to determine the most economical number of items a business should order to reduce costs [Ouyang et al. 2005; Li et al. 2015].

Recently, many papers have presented a supply chain model with blockchain technology or circular economy framework. Table 1 describes the similarities and differences of the developed model with other publications on similar topics. Motivated by the research gap from the literature review, this paper focuses on building a circular economy supply chain model under the influence of blockchain technology and optimizing manufacturers' profits.

Table 1. Recent studies of circular supply chain model with blockchain technology

Article	Circular Economy	Blockchain Technology	Inventory Model	Customer Factors	Solution Method	Key Findings
Chinnaraj and Antonidoss [2021]	No	Yes	Yes	No	Average fitness-based colliding bodies optimization	Optimal inventory management in a secure manner under the cloud sector
Liu et al. [2021]	No	Yes	No	No	Systematic literature analysis	Construction of a blockchain-based maritime supply chain system
Ma and Hu [2022]	Yes	Yes	No	No	Algebraic procedure	Integration of blockchain and sales format in an internet-based platform
Park and Li [2021]	No	Yes	Yes	No	Systematic literature analysis	Application of blockchain technology in sustainable supply chain
Ghoushchi et al. [2021]	Yes	No	Yes	No	Epsilon-constrained method	Strategies of economic order to the suppliers and third-party companies
Sarkar et al. [2022]	Yes	No	Yes	No	Algebraic procedure	Reducing carbon emissions and total costs
Atabaki et al. [2020]	Yes	No	Yes	No	Possibilistic programming approach	Strategic, tactical, and operational decisions in the supply chain network
Suhandi and Chen [2023]	Yes	No	Yes	Yes	A generalized reduced gradient algorithm	Feasibility of the drug recycling program
Saurabh and Dey [2021]	No	Yes	No	No	Conjoint value analysis	Adoption factors for the wine supply chain
Pakseresht et al. [2022]	Yes	Yes	Yes	No	Statistical analysis	Key factors for blockchain-based food supply chain model
Giovanni [2022]	Yes	Yes	Yes	Yes	Structural equation modeling and least squares-path modeling	Blockchain makes supply chains transparent and traceable
Govindan et al. [2023]	Yes	No	No	No	Epsilon-constrained method	Reducing transport emissions and vehicle waiting time
Our work	Yes	Yes	Yes	Yes	Adaptive particle swarm optimization	An optimal strategy for product price and the number of raw materials ordered from the supplier in the circular supply chains under the blockchain framework

PROBLEM FORMULATIONS AND DYNAMIC MODELING

The circular economy research field and a sustainable business strategy are evolving rapidly. Since all companies have finite resources, the reuse and recycling of materials help companies make their production line always have resources available for production, ensuring sustainability. The manufacturer might use an online store to trade products with the shipping company. The online store lets customers contact the manufacturer's customer service directly and quickly. Customers only need to notify the exchange on the online store, and the manufacturer will plan and implement the exchange as soon as possible. Shipping information will also be available online through a partnership between the carrier and the manufacturer. Apart from the production line, the manufacturer might also open a recycling center to receive the used products of customers and conduct product analysis to retrieve reusable parts for the next production. The manufacturer can get materials for production from the supplier and the recycling center. Figure 1 describes the circular supply chain model for reserving resources by reducing, reusing, and recycling.

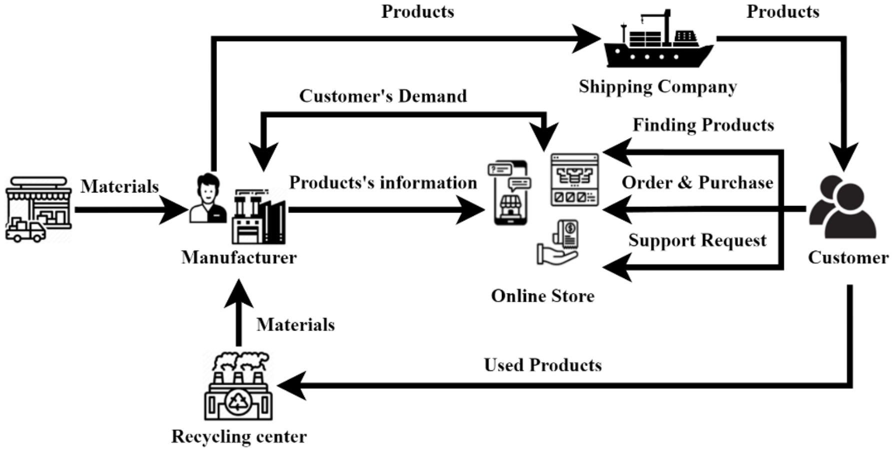


Fig. 1. Circular economy adoption in supply chain management

In addition, the supply chain model employs blockchain technology to ensure the safety and visibility of online transactions. Transactions on the blockchain framework become transparent and traceable as transaction data is stored and distributed across supply chain network participants. The implementation of blockchain technology will give customers a sense of security. Besides that, the origin of the materials that make up the products can also be easy to check. Also, the transparency in the blockchain supply chains helps manufacturers, suppliers, or carriers to check the estimated shipping times. As described in Figure 2, promising blockchain technology can offer possible applications related to operations and supply chain management.

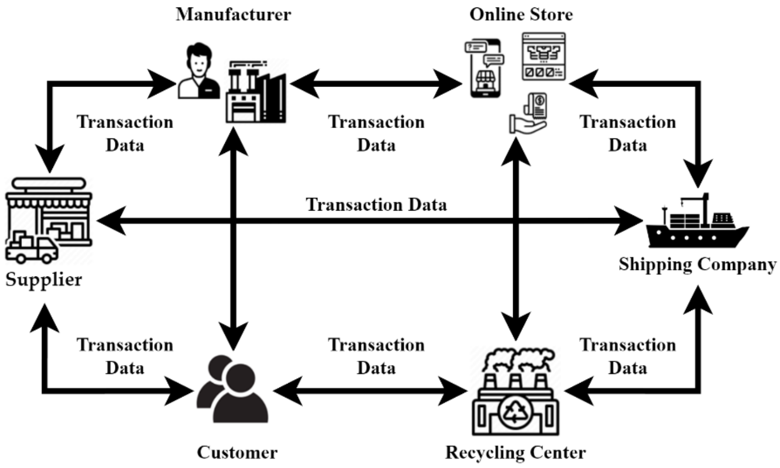


Fig. 2. Generic diagram of blockchain supply chain model

This paper aims to find the product costs and materials order strategy that optimizes the total profit of supply chain management in blockchain and circular economy practices. The traditional supply chain model will be shifted to a more circular economy with a blockchain concept, ensuring waste elimination, keeping materials in use for longer, avoiding the consumption of finite resources, and keeping transaction data safe. The mathematical notation and symbols are summarized in Table 2.

Table 2. Notations and descriptions for the supply chain model

Symbol	Definition	Unit
$D(t)$	Customer demand at a time t	Item
$u(t)$	Production rate at a time t	Item/time
$I(t)$	Inventory level at a time t	Item
$p(t)$	Product unit price at a time t	USD
$m_s(t)$	Number of materials ordered from the supplier at a time t	Item
$m_r(t)$	Number of materials recycled at a time t	Item
X	Random variable affecting customer demand	None
Y	Random rate of the defective product's appearance	None
$N_u(t)$	Number of used products	Item
H	Holding cost	USD
O	Ordering cost	USD
R	Recycling cost	USD
DC	Discount cost	USD
TP	Total profit	USD
h	Holding cost per unit of the product	USD
o	Ordering per unit of the product	USD
r	Recycling cost per unit of the product	USD
v	Discount price per unit of the product	USD
η	Discount rate	None
T	Cycle time of the inventory model	Month

Before presenting the mathematical model, the assumptions will be given below:

1. Customer demand is a random variable.
2. In production, there is a rate of damaged and substandard products.
3. Raw materials are converted into products at a specific rate.
4. Used products would be recycled into raw materials at a specified rate.
5. The cost of ordering materials can be influenced by customer demand.
6. There is no shortage in the inventory.

The transaction data is distributed across the participants in the supply chain network. Customers can quickly check information on the source of materials for the production cycle to collect used products, production standards, and customer service. Thus, these factors can directly or indirectly affect customer demand $D(t)$. In addition, customer demand decreases over time and is inversely proportional to the product unit price $p(t)$. Many unknown factors, such as political conflicts, war, and pandemics, disturb global supply chains. This paper describes the demand uncertainty by a random variable X distributed normally with mean μ_X and standard deviation σ, or $X \sim N(\mu_X, \sigma^2)$. Modern supply chain operations might involve stochastic demand fluctuations under unpredictable markets. The random demand $D(t)$ can be described as follows:

$$D(t) = \lambda(D(0) + Ae^{-(qt+gp)}) + X \quad (1)$$

where A, q, g, and λ are the coefficients. $D(0)$ is the value of customer demand at $t = 0$ (time period). The coefficient impacting customers λ is the value that shows the customer's interest in the manufacturer's product. As illustrated in Figure 2, the information about the transaction data is shared with each component in the supply chain network, ensuring transparency and security. Then the customer can quickly check the information about the materials' origin, the recycling center's operation, and the benefit of returning the used products. The value of λ is derived from surveying a large number of different customers based on the events making them interested in the manufacturer's supply chain,

$$\lambda = K_1 + K_2 + K_3 + K_4 + K_5 = 1, 0 \leq K_1, K_2, K_3, K_4, K_5 \leq 1 \quad (2)$$

where the coefficients (K_1, K_2, K_3, K_4, and K_5) indicate the attraction of the source of the materials, the production standards, the purpose of using used products, the environment's contribution, and the customer support policies, respectively. After serving the customer request, the inventory level in the manufacturer refers to the number of goods or raw materials held by the premises of a business. In the production process, sometimes there are damaged products or products of poor quality to serve customers. A random variable Y expresses the rate of occurrence of defective products in the production process and can be described by a normal distribution with mean μ_Y and standard deviation σ. Based on the production rate and customer demand, the inventory level is characterized by,

$$I(t) = I(t-1) + (1-Y)u(t) - D(t) \quad (3)$$

In this formulation, the defective rate Y is so volatile that decision-makers can hardly handle it in general. The production rate is the number of products that can be produced at a time t, and the production rate $u(t)$ is described as follows:

$$u(t) = \gamma(m_s(t) + m_r(t)) \quad (4)$$

where the coefficient γ represents the conversion rate from materials to products. The materials from the recycling center depend on the number of the used products returned from customers, and one used product can be recycled into α materials,

$$m_r(t) = \alpha N_u(t) \quad (5)$$

The number of used products returned from customers is affected by the manufacturer's purpose of collecting the used products, the environmental contribution, and the customer support policies. The coefficient β is introduced to describe the influence of customers on the decision to exchange used products. It is expressed as a combination of the coefficients (K_3, K_4, and K_5) to form complex scenarios. Then, the number of used products is given by

$$N_u(t) = \beta D(t) = (K_3 + K_4 + K_5)D(t) \quad (6)$$

Policymakers must pay attention to the costs incurred during the operations to manage the supply chain network. One popular way to optimize inventory management is to use the economic order quantity (EOQ) model, which might determine the optimal order quantity to minimize costs and maximize profits. As a metric used in logistics and supply chain management, this model can be employed to determine the unit volume and order frequency needed to satisfy a specific level of demand. Three main factors are crucial in formulating the EOQ model when the market fluctuates: holding cost, ordering cost, and shortage cost. A comprehensive pathway for the transition to a more sustainable system focuses on eliminating waste and the continual use of resources. The inventory-related costs include holding, ordering, recycling, and discount costs. A firm's holding cost is the expenditures used for storing the products in the warehouse, costs for equipment maintenance, warehouse fees, and labor costs. The holding cost can be represented as follows:

$$H = \sum_{t=1}^{T} hI(t) \tag{7}$$

The ordering costs are the expenses used to order raw materials from suppliers, including purchasing materials, transportation, etc. The supplier can also track the manufacturer's product consumption through the transaction information shared by the blockchain network; therefore, the cost of ordering materials can also be affected, depending on the customer demand of the manufacturer. ψ is the coefficient indicating the change in customer demand for the ordering cost. The ordering costs are described by,

$$O = \sum_{t=1}^{T} oe^{\psi D(t)} m_s(t) \tag{8}$$

The recycling policy promotes reutilizing materials and reducing waste for production. For recycled materials or reusing materials to manufacture their products, the recycling cost includes transportation costs to get the used products from customers, operation costs, labor charges, etc.,

$$R = \sum_{t=1}^{T} r\beta D(t) \tag{9}$$

The discount cost is the loss due to pricing adjustments designed to increase sales,

$$DC = \sum_{t=1}^{T} v\alpha\beta D(t) = \sum_{t=1}^{T} \eta p(t)\beta D(t) \tag{10}$$

By considering various cost parameters, the objective function or fitness function is to maximize the total profit in the overall supply chain,

$$\begin{aligned} TP &= \max_{p,m_s}\left\{\sum_{t=1}^{T}\left(p(t)D(t)-\left(H+O+R+DC\right)\right)\right\} \\ &= \max_{p,m_s}\left\{\sum_{t=1}^{T}\left(p(t)D(t)-\left(hI(t)+om_s(t)+r\beta D(t)+\eta p(t)\beta D(t)\right)\right)\right\} \end{aligned} \tag{11}$$

In this optimization problem, some parameters are described as random variables. The supply chain system is simplified by assuming that the inventory quantity is always positive and there are no shortages. The dynamic inventory model focuses on determining the unit price or the number of raw materials needed from suppliers to optimize profits rather than calculating factors to maintain a positive inventory. The heuristic algorithm is presented to deal with the optimization problem.

HEURISTIC OPTIMIZATION APPROACH

As described, the customer demand $D(t)$ and the inventory level $I(t)$ represent mixtures of randomness and uncertainty depending on the random variables X and Y, respectively. The objective function in Equation 11 has an inherent uncertainty that relies on a set of random variables. In this paper, a metaheuristic algorithm must be generic and practical such that it is used to solve fitness functions containing random variables. The adaptive particle swarm optimization (APSO) algorithm is the heuristic search technique tuned by trial and error to solve function optimization problems. The heuristic algorithm starts with initializing a swarm with a specified number of particles at different positions in the search space. Each particle will give one solution for the fitness function. This paper aims to optimize the total profit of the supply chain model under uncertainty. The adaptive PSO algorithm is executed in a predefined number of iterations for an efficient optimization problem solution. In the first iteration, each solution given by one particle will compare with the others and find the largest value of the objective function. Then the solution and the particle will be saved for reference in the next iteration. The best solution in one iteration is called the local best value. The best solution on all iterations is called the global best value. The final search result will be the global best value and the corresponding particle's position at all other feasible points. At the beginning of each iteration, the position of each particle will change its direction with the rate as the formula is given below,

$$V_i^{j+1} = wV_i^j + c_1 b_1 \left(L_{localbest}^j - L_i^j \right) + c_2 b_2 \left(L_{globalbest} - L_i^j \right) \tag{12}$$

$$L_i^{j+1} = L_i^j + V_i^{j+1} \tag{13}$$

where V_i^j is the velocity of the particle i at iteration j; L_i^j is the position of the particle i at iteration j; w is the inertia weight, $w > 0$; c_1 and c_2 are the learning rates, $c_1, c_2 > 0$; b_1 and b_2 are the random constants, $b_1, b_2 \in [0,1]$; $L_{localbest}^j$ is the best solution in one iteration; $L_{globalbest}^j$ is the best solution on all iterations. Equation (12) represents the velocity, which makes the particles change their position in each iteration. Equation (13) determines the next position of the particle L_i^{j+1}. The inertia weight w is the positive constant, affecting the speed and direction. The learning rates (c_1 and c_2) make the particle move towards the direction with the best solution. The parameters b_1 and b_2 are distributed with the $[0, 1]$ range, maintaining their normal-like shapes. In iterative search, each particle gives one solution for the fitness function. The result is more likely to be trapped in a local optimum position in the standard PSO algorithm, especially in high-dimensional problems. The adaptive PSO algorithm has been presented to overcome this problem to improve search efficacy and convergence speed. In this strategy, the inertia weight w, the local learning rate c_1, and the global learning rate c_2 will be changed in each iteration to help the algorithm find the optimal point faster and avoid convergence to the local optimal point,

$$w^{j+1} = w_0 \left(1 - \frac{L_{localbest}^j}{L_{globalbest}^j} \right)^2, c_1^{j+1} = c_{1,0} \left(1 + \frac{L_{localbest}^j}{L_{globalbest}^j} \right)^2, c_2^{j+1} = c_{2,0} \left(1 + \frac{L_{localbest}^j}{L_{globalbest}^j} \right)^2 \tag{14}$$

where the parameters w_0, $c_{1,0}$ and $c_{2,0}$ are the initial values of w, c_1 and c_2, respectively. The algorithm will update the parameter values (w, c_1, and c_2) based on the difference between the local optimal value $L_{localbest}^j$ and the global optimal value $L_{globalbest}^j$. When the local optimal value is near the global optimal one for a specific search space region, the weight value w will be decreased to focus on the search region that contains the global optimal value and make little adjustments to find it faster. Conversely, the values of c_1 and c_2 will increase as the local optimal value is closer to the global optimal value. Increasing the values of c_1 and c_2 will help the algorithm speed up the search for the optimal value at all other feasible points. Specifically, the optimization problem in this paper is to determine the unit price of the product and the number of materials that need to be imported from outside suppliers to optimize the total profit. Two separate sets of particles need to be initialized at the start of the optimization process. One is the set of particles representing the product's unit price, and the other is the set of particles representing the number of materials to be imported. The algorithm and pseudocode are presented in Table 3.

Table 3. Pseudocode algorithm for adaptive PSO strategy

Pseudo code for the adaptive PSO algorithm

Initialize particles 1 (p);

Initialize particles 2 (m_s);

Initialize the local best solution ($BestLocal$);

Initialize the global best solution ($BestGlobal$);

for j = 1: maximum iteration

  for i = 1: maximum population size

    $\text{BestProfit} = TP\left(L_{i,p}^{j}, L_{i,m_s}^{j}\right)$;

    if $\text{BestProfit} \geq \text{BestLocal}$

      $\text{BestLocal} = \text{BestProfit}$;

      $\text{BestPrice} = L_{i,p}^{j}$;

      $\text{BestMaterials} = L_{i,m_s}^{j}$;

    End

    $V_{i,m_s}^{j+1} = wV_{i,m_s}^{j} + c_1 b_1 \left(L_{localbest,m_s}^{j} - L_{i,m_s}^{j}\right) + c_2 b_2 \left(L_{globalbest,m_s}^{j} - L_{i,m_s}^{j}\right)$;

    $L_{i,m_s}^{j+1} = L_{i,m_s}^{j} + V_{i,m_s}^{j+1}$;

    $V_{i,p}^{j+1} = wV_{i,p}^{j} + c_1 b_1 \left(L_{localbest,p}^{j} - L_{i,p}^{j}\right) + c_2 b_2 \left(L_{globalbest,p}^{j} - L_{i,p}^{j}\right)$;

    $L_{i,p}^{j+1} = L_{i,p}^{j} + V_{i,p}^{j+1}$;

    $w^{j+1} = w_0 \left(1 - \frac{L_{localbest}^{j}}{L_{globalbest}^{j}}\right)^2$;

    $c_1^{j+1} = c_{1,0} \left(1 + \frac{L_{localbest}^{j}}{L_{globalbest}^{j}}\right)^2$;

    $c_2^{j+1} = c_{2,0} \left(1 + \frac{L_{localbest}^{j}}{L_{globalbest}^{j}}\right)^2$;

  end

  if $BestLocal \geq BestGlobal$

    $BestGlobal = BestLocal$;

    $\text{BestPrice} = L_{i,p}^{j}$;

    $\text{BestMaterials} = L_{i,m_s}^{j}$;

  end

end

NUMERICAL EXPERIMENTS

The proposed framework is intended to yield a more sustainable, resilient, and regenerative system, securing the data of the shared community. Numerical experiments are conducted to verify the effectiveness of inventory optimization schemes. The numerical simulations are performed using MATLAB environment on Windows 10 Pro 64-bit computer, 16GB RAM, and AMD Ryzen 5 5600G processor with Radeon Graphics. The adaptive swarm optimization method evaluates the fitness function involving discrete random variables. Supply chain management captures the realistic conditions by considering the inherent uncertainties of customer demand. The influence of the number of used products on the optimal strategy is analyzed to maximize the total profit in the cycle T . The experimental settings and conditions are described below in detail. The online store receives the customer demand, $D(1) = 1000$ items and sends them back to the manufacturer. The random variable X represents the uncertain event that affected customer demand. It has the value from $[-200, 200]$ items, with the normal distribution, $X \sim N(0,1^2)$. The manufacturer plans to import raw materials and produce the product for a period of 12 months, or $T = 12$ (months). The recycling center accepts requests to return the used products to manufacturers through the online store. For each returned used product, the customer can receive a discount rate on the unit price of the product, $v(t)=0.1p(t)$. In the production process, the random variable Y represents the rate of occurrence of defective products. It has the value from $[0,0.2]$ and follows the normal distribution, $X \sim N(0.1,1^2)$. In the production line, it is assumed that one product is made from five materials, $\gamma=1/5$. In the recycling center, one used product can be recycled into two materials used for production, $\alpha=2$. The holding cost for one product is given in $h=20$ (USD). The ordering cost for one material is $o=30$ (USD). Using blockchain transaction information, the manufacturer can adjust the ordering cost according to customer needs with the influence of the coefficient $\psi=0.0001$. The recycling cost for one used product is $r=15$ (USD). The numerical experiment considers two scenarios to assess the impacts of returned used products on the supply chain network. In Scenario 1, the coefficient (λ) impacting customers has the following components: 35% the number of customers interested in the origin of raw materials, or $K_1=0.35$, 25% number of customers for the production's standard, or $K_2=0.25$, 20% number of customers for the collecting used products, or $K_3=0.2$, 10% number of customers for the environment's contributions, or $K_4=0.1$, and 10% number of customers for the customer services, or $K_5=0.1$. The coefficient indicates the influence of customers on the decision to exchange used products in Scenario 1, or $\beta=K_3+K_4+K_5=0.4$. In Scenario 2, the coefficients are similarly selected as follows: $K_1=0.1, K_2=0.1, K_3=0.3$, $K_4=0.2$, and $K_5=0.3$, or $\beta=K_3+K_4+K_5=0.8$. The number of returned used products in Scenario 2 is greater than in Scenario 1. In summary, the key parameters, along with the numerical scenarios used in this test, are listed in Table 4.

Table 4. Summary of the experimental settings

Parameter	Scenario 1	Scenario 2	Parameter	Scenario 1	Scenario 2
$D(0)$	1000 items	1000 items	K_2	0.25	0.1
$I(0)$	1100 items	1100 items	K_3	0.2	0.3
A	-75	-75	K_4	0.1	0.2
q	0.3	0.3	K_5	0.1	0.3
g	0.2	0.2	β	0.4	0.8
γ	0.2	0.2	w	1	1
α	2	2	c_1	0.001	0.001
h	20 (USD)	20 (USD)	c_2	0.001	0.001
o	30 (USD)	30 (USD)	w_0	1	1
r	15 (USD)	15 (USD)	$c_{1,0}$	0.1	0.1
η	0.1	0.1	$c_{2,0}$	0.1	0.1
ψ	0.0001	0.0001	Number of population	25	25
T	12 (months)	12 (months)	Maximum iteration	250	250
K_1	0.35	0.1			

Now, the proposed optimization problems can be solved by an adaptive PSO algorithm. As shown in Figure 3, the maximum total profits that the manufacturer can achieve after 12 months in Scenario 1 and Scenario 2 are 1867383 (USD) and 1287409 (USD), respectively.

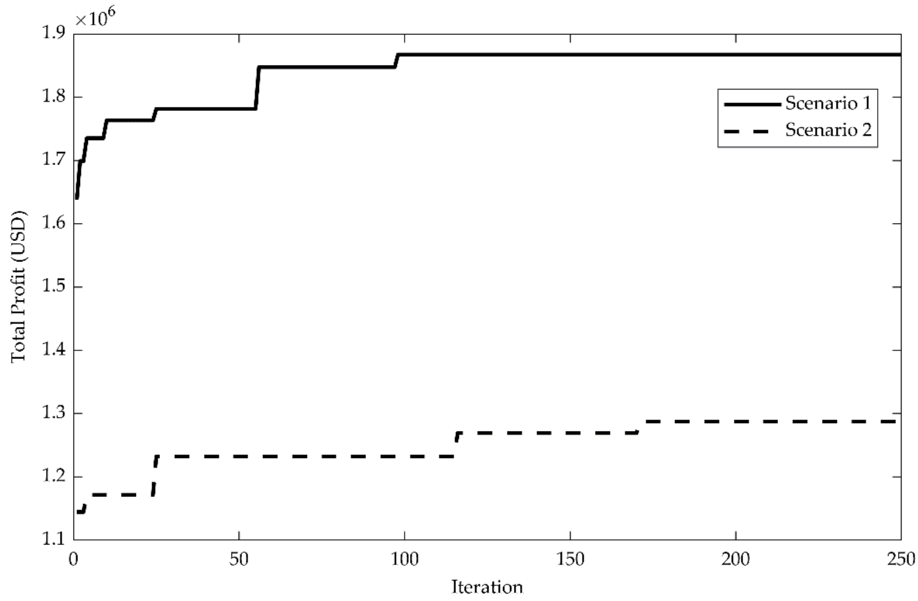


Fig. 3. Total profits achieved under heuristic algorithm.

Two scenarios in business settings have been tested on the same customer demand. However, the number of used goods returned in Scenario 2 is more than in Scenario 1, resulting in more inventory than in Scenario 1. This study assumes that there is no shortage in the inventory. The negative value implies that the inventory value will be set to zero. The inventory level of Scenario 2 is always greater or equal to that of Scenario 1. Holding a lot of inventory at one time will likely impose high carrying costs, leading to reduced profits in Scenario 2. The inventory levels and profits are illustrated in Figure 4.

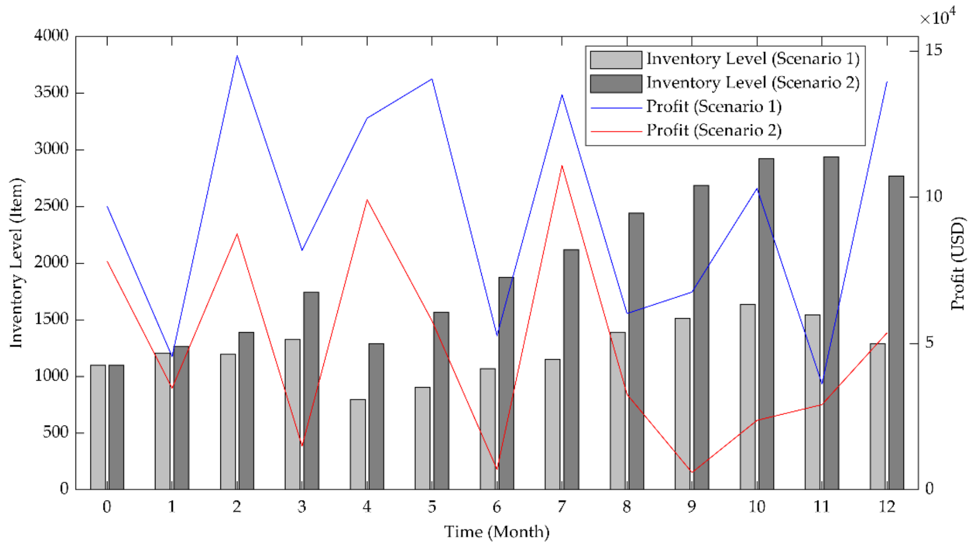
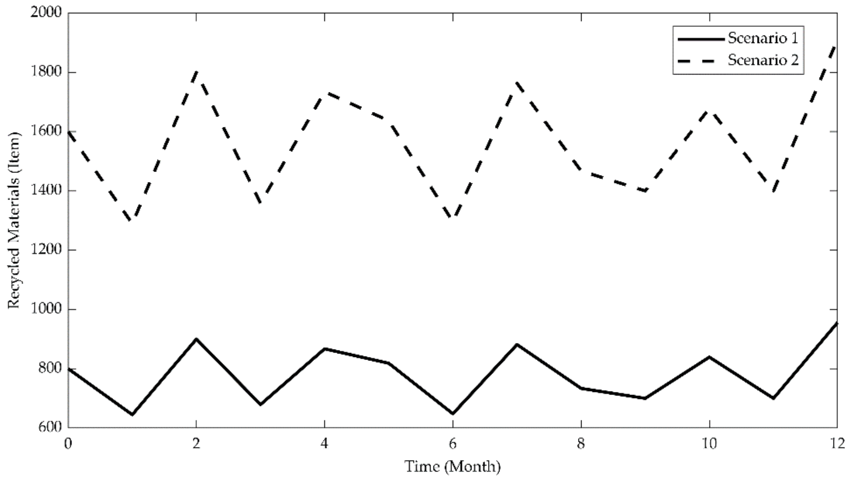
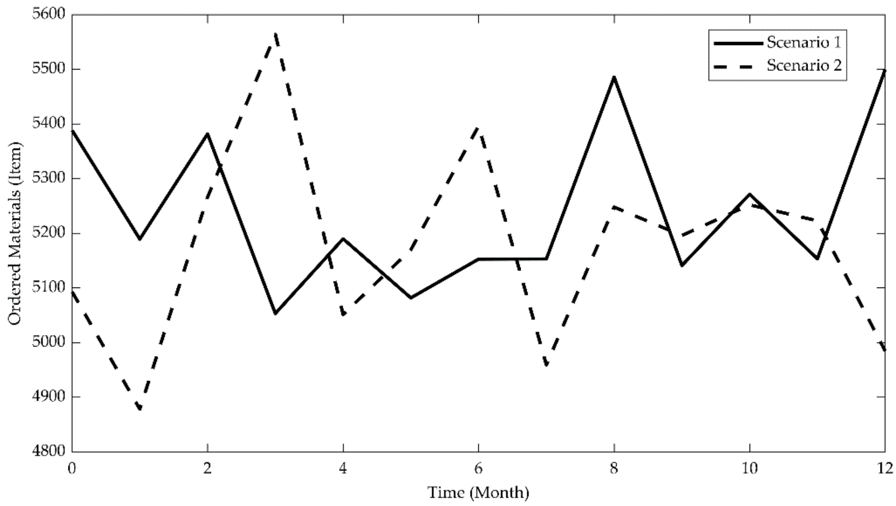


Fig. 4. Time history of inventory levels and profits

Figure 5(a) shows the number of recycled materials in two scenarios. Since the number of used products returned in Scenario 2 is greater than in Scenario 1, the number of recycled materials in Scenario 2 is also greater than in Scenario 1. As illustrated in Figure 5(b) and Table 5, the optimal numbers of ordered materials in both methods are not so different. There is no statistically significant variation.



(a)



(b)

Fig. 5. Time history of ordered and recycled materials in two scenarios: (a) number of recycled materials, (b) an optimal number of ordered materials.

Table 5. The optimal number of ordered materials

Scenario 1	Month	0	1	2	3	4	5	6
	Number of ordered materials (item)	5389	5190	5382	5053	5190	5082	5153
	Month	7	8	9	10	11	12	
	Number of ordered materials (item)	5153	5486	5142	5272	5154	5500	
Scenario 2	Month	0	1	2	3	4	5	6
	Number of ordered materials (item)	5094	4879	5267	5565	5052	5170	5397
	Month	7	8	9	10	11	12	
	Number of ordered materials (item)	4960	5249	5197	5253	5223	4985	

The optimal price strategy in both scenarios is shown in Figure 6, and the detailed values are shown in Table 6. The optimal number of ordered materials and the optimal product price are two decision variables that will lead to the best total profit of the supply chain model.

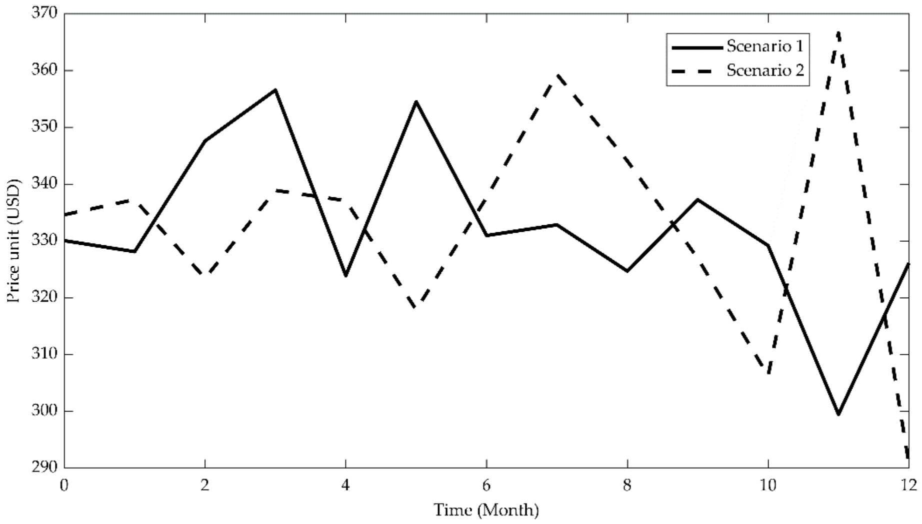


Fig. 6. Optimal product price

Table 6. Value of the optimal product unit in each month

Scenario 1	Month	0	1	2	3	4	5	6
	Price unit (USD)	330.05	328.12	347.59	356.56	323.90	354.51	330.95
	Month	7	8	9	10	11	12	
	Price unit (USD)	332.83	324.68	337.25	329.18	299.47	326.09	
Scenario 2	Month	0	1	2	3	4	5	6
	Price unit (USD)	334.60	337.28	323.42	338.90	337.09	317.87	337.66
	Month	7	8	9	10	11	12	
	Price unit (USD)	359.33	344.09	326.95	306.25	366.61	290.82	

With the given customer demand, the total profit in Scenario 1 is higher than in Scenario 2 (Figure 3). In Scenario 2, the number of used products returned is more significant than in Scenario 1. The average number of used products in Scenario 1 has nearly doubled in Scenario 2 due to the value of β in each scenario, leading to increased recycling costs and fees for publishing discount vouchers to customers. However, the increase in the number of used products returned makes manufacturers hold an abundant source of materials for production. The increase in the number of used products returning to the recycling center might result in fewer ordered materials for Scenario 2 than for Scenario 1. Because of holding more inventories (Figure 4) and recycling more used products (Figure 5a) than Scenario 1, the unit price of Scenario 2 is higher than Scenario 1. The unit price in Scenario 1 equals nearly 98.64 percent of the unit price in Scenario 2. Increasing the number of raw materials by recycling used products might not bring advantages in terms of profits. However, it can diversify the source of raw materials for production, avoiding resource shortages. The extensive numerical results demonstrate that the presented strategy can offer more robust supply chain management under uncertainty where the quality or quantity is subject to frequent, rapid, and significant changes.

DISCUSSION AND MANAGERIAL INSIGHTS

Critical issues for the *development* of an effective *SCM strategy* are discussed as follows. The numerical experiments have provided numbers and charts illustrating the impact of circular supply chain management with blockchain integration, demonstrating an essential building block for sustainability targets. The manufacturers utilized used products for recycling into raw materials for the next production stage through the recycling center. Sharing, reusing, repairing, and remanufacturing help companies transition to a circular economy, minimize waste, diversify sources of supply, and maintain production continuity. Previous studies only deal with the relationship between incentives and product returns without considering factors such as recycling used products or the effect of the number of materials or products imported from outside.

There are many ways to motivate customers to return used products to the manufacturers, such as issuing discount vouchers, positively contributing to environmental protection, and creating convenience for users when they want to return products through online customer services. The information between parts of the supply chains is connected by blockchain technology, enabling customers to identify the origin of the materials, the purpose of collecting secondary materials of the manufacturer by names, and information of departments that receive and process transactions. In this circular economy supply chain model, the customer's perspective can influence demand and determine the number of used products a recycling center can receive. The more used products the recycling center receives, the more secondary materials can be recycled. In the numerical experiments, the difference between the two scenarios is the coefficient beta, which describes the influence of customers on the decisions to exchange used products. In Scenario 1, the beta (β) is 0.4, corresponding to the number of used products returned to the recycling center, equaling 40 percent of the sold products. The beta in Scenario 2 is 0.8. The difference between the coefficient beta in the two scenarios presents the variance in the number of recycled materials described in Figure 5a. Acquiring more recycled materials might reduce the quantity of materials imported from suppliers. It is noted that the ordered materials for Scenario 2 are 5.48 percent less than Scenario 1. Diversifying the sources of raw materials helps manufacturers always have materials to maintain their production activities, lowering costs, increasing productivity, improving sustainability, and enhancing innovation. However, the manufacturers should have to bear other costs. To attract customers to return used products, they need to give a discount voucher of 10 percent for the next purchase for each used product returned by customers. To optimize the profit that the manufacturer can achieve, the product unit price of Scenario 2 is 1.37 percent higher than Scenario 1 due to a higher recycling fee and discount fee. If the customer demand in Scenario 2 is the same as Scenario 1, the total profit of Scenario 1 is higher than Scenario 2 (Figure 3).

Typically, no single model *suitably fits all* businesses under *every circumstance* for the decision support system in the managerial field. Therefore, a flexible selection from a generic strategy is crucial for decision-makers. This paper does not consider a specific product but focuses on building a circular supply chain model for generic items under the influence of blockchain technology. Based on the above analysis, a circular supply chain model can help manufacturers use secondary materials to reduce costs when ordering materials from outside suppliers. However, manufacturers must offer promotions or gifts based on the number of returned products to attract customers to return used products. The proposed approach usually works best but *has some* obvious *limitations* that should be improved in future research. The manufacturer must control the number of used products to achieve the desired total profit. Furthermore, having an additional source of raw materials from the recycling center will help manufacturers diversify their supply, enhancing their ability to maintain production even in the event of a shortage of raw materials in the market.

CONCLUSION

The circular economy might provide a systematic path to ensuring supply chain sustainability and reducing environmental harm. The recycled materials will be alternative sources of raw materials for producing or manufacturing goods. In the context of increasing digital technology, online stores as retailers can simplify product selection procedures and customer payments. Recently, transparency in transactions and the security of decentralized systems have been focused on in the field of information security, providing the potential to reduce inventory management risk. Applying blockchain technology to supply chain transactions can help the participants better trace transaction data and create trust for customers. Based on the circular economy and blockchain platform, this study deals with an adaptive particle swarm optimization algorithm (APSO) to determine the optimal strategy for product unit price and quantity of materials imported from suppliers to maximize total profits. The supply chain model incorporates realistic market conditions by considering the inherent uncertainties of customer demand. In the stochastic optimization problem, some parameters are described as random processes. This paper aims to examine the secure and decentralized business strategy of product pricing and the number of ordered materials for the circular supply chains to bring the optimal profit for the manufacturer and analyze the effect of the number of returned used products on total profits. The numerical test results are presented to verify the efficacy of a novel decision-making policy offering exceptional performance and reliability. Based on comparison with experimental data, it is shown that the amount of recycled used products affects the producer's profitability. Recycling too many used products has increased recycling costs and holding costs. However, it can reduce the manufacturer's dependence on external material suppliers, diversify the sourcing of raw materials, and hedge against material scarcity issues. Furthermore, all validation tests *ensure that* the proposed decision support system can aid policymakers in managing stochastic supply chain systems with minimal effort and adopting novel *strategies* to ensure resilience and customer satisfaction. Finally, the key findings significantly contribute to the intelligent decision support system for optimizing inventory management under various stochastic scenarios.

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ORIGINAL PAPER

SUPPORTING THE INVENTORY MANAGEMENT IN THE MANUFACTURING COMPANY BY CHATGPT

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ABSTRACT. Background: The decision-making process in the operational context of enterprises is an integral aspect of how they function, and in this area, precise demand forecasting plays a key role. The use of accurate forecasting models not only meets customer expectations but also enables efficient resource allocation and operational cost optimization. In the long term, such actions contribute to increasing the organization's competitiveness in the market. In recent years, there has been a growing trend in the use of advanced analytical technologies, including machine learning, for demand forecasting purposes. This scientific paper focuses on a comparative analysis of demand forecasting effectiveness using the generative language model GPT in relation to the auto ARIMA algorithm.

Methods: A case study analysis for a selected manufacturing organization was conducted based on twelve diversified operational references, for which the supply chain mechanisms are heterogeneous. In the research process, a classification into four reference groups was established, based on the time required to complete the ordering process. Forecast generation was carried out using the auto.arima() algorithm in the R programming environment, as well as through the ChatGPT language model versions 3-5. The forecast results were subjected to comparative analysis, in which weighting was applied for different forecast accuracy indicators, including the Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and the number of precisely predicted daily forecasts.

Results: The study showed that ChatGPT is more reliable in forecasting compared to ARIMA. However, integrating ChatGPT into the existing systems in the company can be problematic, mainly due to limitations in data operations. Despite this, ChatGPT has the potential to improve the accuracy of inventory management plans both in the short and long term.

Conclusions: The comparative analysis of the effectiveness of forecasting models, including ChatGPT and ARIMA, showed that the ChatGPT algorithm achieves higher levels of forecasting accuracy. This is observed despite increased computational complexity and challenges associated with processing large data sets.

Keywords: ARIMA, ChatGPT, demand forecasting, inventory management

INTRODUCTION

Issues related to assortment management are highly significant, particularly for manufacturing companies whose production activities are often heavily reliant on a well-structured and functioning supply system (Phan et al., 2019). With dynamic changes in customer preferences, increasing competition, and rapid technological advancements, businesses must develop modern assortment management methods that can forecast product demand effectively. Demand forecasting is a crucial element of efficient assortment management in manufacturing companies (Sharma and Singhal, 2019). Accurate forecasts enable process optimization, minimize inventory costs, avoid excess stock, and fulfill customer needs quickly and efficiently. In recent years, numerous modern methods and tools have emerged to support companies in forecasting product demand. One such tool involves utilizing advanced machine learning algorithms, including predictive models based on artificial intelligence (Makridakis et al., 2018; Ahmed et al., 2010). These models can analyze vast amounts of historical data, taking various factors into consideration, such as market trends, seasonality, promotions, and customer

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preferences, thus leading to more precise demand forecasts.

In recent times, we are also witnessing a rapid development of advanced machine learning and artificial intelligence-based language models (Dillon et al., 2023), which are increasingly seen as applicable in various domains of life and industry. One of the most popular language models today is ChatGPT. ChatGPT is a language model that utilizes powerful machine learning algorithms to generate responses to user queries in a natural and interactive manner. According to many authors, ChatGPT has a significant impact on the business sector (George and George, 2023). In this article, the authors focus on examining the performance of ChatGPT in forecasting the demand for references used in production, based on a selected case study.

THEORETICAL BACKGROUND

Meaning of assortment management

Assortment management is a critical aspect of logistics management, which involves managing the inventory of products and services offered by a company to meet the diverse needs and preferences of its customers. According to Waßmuth et al. (2023), assortment management involves selecting the right mix of products and services that can generate maximum revenue and profit for the company, while also meeting the demand and expectations of customers. Inventory management is also a key area of logistics coordination (Kmiecik, 2022b): on the one hand, it aims to reduce unforeseen fluctuations in demand and ensure an appropriate level of customer service in distribution networks; on the other, it is an area that largely depends on the adopted strategies for planning and implementing demand plans (Abdolazimi et al., 2021). The primary goal of assortment management is to optimize the product mix by selecting the right products, at the right time, and in the right quantities to meet customer demand and improve the overall profitability of the company (Dantu and Vasudevan, 2021). This requires a deep understanding of customer preferences, market trends, and supply chain dynamics. Companies need to analyze customer data, such as buying patterns, purchase history, and demographics, to identify the most profitable products and services and tailor their assortment accordingly. Proper handling of inventory management also has a positive impact on supply chain sustainability (Paam et al., 2019) because the coordination in the case of inventory management allows, among other things, for a reduction in the supply level in the whole network and minimizes the waste in stocks. Assortment management can also help companies to manage their inventory efficiently, reduce stock-outs, and improve customer satisfaction. According to Gupta and Ramachandran (2021), effective assortment management can help companies to reduce the cost of inventory holding and improve the availability of products to customers, thereby enhancing customer loyalty and retention. An interesting fact is that while stocks are generally held to meet demand, in some situations, they are held to stimulate demand (Murphy and Wood, 2020) through active influence in the sphere of customers, for example. In the literature, this effect is called the psychic stock effect. To achieve effective assortment management, companies need to adopt advanced technologies such as predictive analytics, artificial intelligence, and machine learning to analyze customer data, market trends, and supply chain dynamics (Bartkowiak and Rutkowski, 2016). These technologies can help companies to identify emerging trends, forecast demand, and optimize their product mix, leading to improved profitability and competitiveness in the market. Some logistics enterprises like logistics operators could both manage inventories for the purpose of their effective deployment in particular places in the supply chain and attempt to eliminate the bullwhip effect (Kmiecik, 2022a). These aspects could be positively influenced by the operator's experience in implementing logistics tasks and their ability to react quickly and adapt activities to the requirements of individual cells. In the supply chains, the manufacturing companies are also responsible for proper material handling in the cases of in-house logistics. The present challenge of inventory management is handling demand fluctuations, stockouts and managing the individual SKUs (Stock Keeping Units), while also handling big data (Patil, 2014). Management from the level of individual SKUs is problematic in terms of the amount of data and information that are associated with it. Inventory management based on big data can lead to advantages, such as (Malik and Jeswani, 2018):

- Improving operational efficiency;
- Maximizing profits and sales;
- Increasing customer satisfaction rates;
- Reducing IT infrastructure costs by migrating to the cloud.

Assortment management actions are currently focused on providing plenty of services related directly to inventory and stock management. Inventory management from the perspective of the entire network would enable its efficient coordination by means of planning and implementing assumptions related to the allocation of supplies and their effective use. On the other hand, nowadays we are dealing more and more often with a one-day-delivery standard in transport operations (Grzelak et al., 2019). As mentioned by some authors, through appropriate transport planning, enterprises could reduce flow times and reduce inventory levels (Wang et al., 2021) by increasing the speed of reaction and eliminating the need to maintain high-safety stocks. Assortment management is a critical aspect of logistics management that can help companies to optimize their product mix, reduce inventory holding costs, and improve customer satisfaction. Companies need to adopt advanced technologies and data analytics tools to achieve effective assortment management and stay competitive in the ever-changing business environment.

AI usage at assortment management

Traditional methods of inventory management rely heavily on human decision-making and manual processes. It is strictly connected with the knowledge and skills of specialists who work in the company structures. Of course, even in the traditional approach, the human workers are usually supported by IT systems which facilitate their work. The use of IT systems is aimed at achieving similar results as by using AI (artificial intelligence) and ML (machine learning) technologies. Inventory management supported by AI or ML leverages the power of technology and data analysis to make more accurate and efficient decisions. AI and ML can help businesses make better decisions about their inventory levels, improve their operations, and increase their profitability. Traditional methods of inventory management often rely on historical data and basic forecasting techniques, such as moving averages or trend analysis. AI and ML, on the other hand, can analyze large volumes of data from multiple sources to create more accurate forecasts that consider complex factors such as seasonality, promotions, and even weather patterns. Traditional methods also typically involve periodic checks of inventory levels, which can lead to stock-outs or overstocking, if demand patterns change unexpectedly. AI and ML can continuously monitor inventory levels in real-time and adjust replenishment decisions accordingly, reducing the risk of stockouts and improving efficiency. Traditional inventory management often involves balancing trade-offs between stock levels, service levels, and costs. AI and ML can optimize inventory levels based on multiple factors, such as sales patterns, delivery times, and customer demand, to maximize profitability and minimize waste. Traditional ways often require significant manual effort, such as doing the inventory by hand, entering data into spreadsheets, and creating reports. AI and ML can automate many of these processes, freeing up time for employees to focus on higher-value tasks (Mukhopadhyay et al., 2012).

AI-based systems could be used in the area of inventory management, in the field of demand forecasting, and for modeling inventory management actions (Praveen et al., 2019). AI and ML algorithms can analyze historical sales data and use it to predict future demand for different products. This helps businesses optimize their inventory levels and prevent stock-outs or overstocking. The issue of support demand management is one of the most popular areas of AI usage in the context of AI (Albayrak Ünal et al., 2023). AI and ML can also be used to determine the optimal time to restock inventory. This is done by analyzing factors such as lead times, supplier performance, and customer demand patterns. Some researchers are of the opinion that ML could prove to be an excellent technology for supporting the DSS (Decision Support Systems) in companies (Praveen et al., 2020). AI is used in different areas of forecasting, from predicting air pollution (Masood and Ahmad, 2021), and forecasting load demand forecasting techniques for smart grid and buildings (Raza and Khosravi, 2015). Even the tough years of the COVID-19 pandemic were a great period for developing and testing AI tools for forecasting purposes. For example, Elsheikh et al. (2021) proposed an AI tool for forecasting the pandemic spreading around the world, while other scholars proposed AI tools for forecasting this same issue in particular regions, for example, Hu et al. (2020) in China and Al-Qaness et al. (2021) in Russia and Brazil. Another interesting topic is the possibility of using AI to predict new phenomena through analogy (Lee et al., 2007), which was previously challenging to achieve.

By analyzing leading journals in terms of the Impact Factor (IF) that mainly focus on forecasting, namely Technological Forecasting and Social Changes (2023 IF = 12.00) and the International Journal of Forecasting (2023 IF = 7.90), one can also observe a trend in writing about AI in the context of forecasting, especially forecasting related to material planning and demand. AI in research is being considered for use in sales forecasting (Zhang et al., 2022; Lu et al., 2023), export sales (Sohrabpour et al., 2021), demand for problematic products such as fashion products (Swaminathan and Venkitasubramony, 2023), and demand forecasting across supply chains (Boone et al., 2019). The use of AI in inventory planning is highlighted by Petropoulos et al. (2022) and Huynh et al. (2023), where the relevance of using AI in BigData analysis is often emphasized. AI is also indicated as a suitable solution for purchasing and supply management (Delke et al., 2023).

By analyzing sales data, AI and ML can identify which products are selling well and which are not. This allows businesses to adjust their inventory levels and focus on the products that are most profitable. In addition to this, a great deal of research shows that AI or solutions connected with AI like ANN (Artificial Neural Network) could support inventory classification. Even in the early 2000s, some authors tried to use ANN for inventory classification (Partovi and Anandarajan, 2002). Currently, the use of ANN and AI for inventory classification remains a problem. These technologies could be used for multicriteria inventory classification as an element that supports the fuzzy AHP (Analytic Hierarchy Process) (Kabir and Hasin, 2013) or multi-criteria ABC analysis (Yu, 2011). AI and ML can be used to monitor equipment and machinery in warehouses and predict when they will need maintenance or repairs. This helps prevent downtime and ensures that operations run smoothly. Such technologies can also be used to identify patterns of fraud in inventory management. By analyzing sales data and identifying anomalies, these algorithms can help businesses detect and prevent fraud. AI could be used to predict and minimize inventory distortions for improving resiliency (Jauhar et al., 2023). Nowadays it is often claimed that AI could replace traditional inventory management systems (Preil and Krapp, 2022; Praveen et al., 2020) and it should be a basic element of Smart Warehouse Management System (Zunic et al., 2018), which gives the opportunity for achieving the better results.

The increasing adoption of social chatbots is unmistakable, and this is chiefly due to their ability to mimic human communication. Very often chatbots are analyzed in terms of raising the level of customer service or different social issues (Malik et al., 2023l Chang et al., 2023). Such chatbots support clear, text-based conversations, often replacing traditional interactions between humans (Ali et al., 2023). Chatbots are also considered to be tools for improving predictions using behaviour modifications (Shmueli and Tafti, 2023). Various researchers agree that the core components of chatbots include AI, machine learning, deep learning, natural language processing, productive and sentimental analytics (Rawat et al., 2022). It is often the case that chatbots are combined with task automation and data gathering systems, bolstered by innovations like the Internet of Things (IoT) (Wu et al., 2018).

These bots are acknowledged to be able to enhance communication between businesses within supply chain structures (Modgil et al., 2022). Their transformative role in communication is especially worth noting in e-commerce, where they often act as AI-driven aids, particularly when introducing novel customer engagement methods during product distribution (Angelov and Lazarova, 2019; Sharma et al., 2022). The demand for voice-operated chatbot platforms tailored for customer interactions across various supply chain stages, like shopping and order processing, is expected to persist in its upward trend in global logistics

(Suvethashri and Vickram, 2019). Through chatbots, supply chains can offer personalized services and improve procurement, client interactions, and transport operations (Modgil et al., 2022; Sai et al., 2022; Wu et al., 2018). Moreover, academic experts indicate that for cost efficiency, logistics firms often opt for chatbots over designing custom apps (Kolosok and Lazarevska, 2020). Incorporating AI-powered chatbots provides customers with digital helpers for queries on order status and delivery schedules, reducing the need for human involvement (Modgil et al., 2022). It is suggested that around 47% of shoppers might have a positive buying experience when using chatbots, and their inherently emotion-free interaction style might reduce customer complaints (Merdin and Ersoz, 2019).

ChatGPT is a prime example of a chatbot that is currently drawing significant attention from both the academic and business communities.

ChatGPT environment

ChatGPT is an innovative artificial intelligence system that was launched in November 2022. GPT stands for Generative Pre-trained Transformer. It is a language model whose task is to generate responses to user queries based on specialized training. ChatGPT was created by the research laboratory OpenAI, dedicated to artificial intelligence research. The laboratory team is based in San Francisco and aims to develop AI that is friendly to humans and brings societal benefits. The pursuit of creating advanced AI tools like ChatGPT has the potential to revolutionize many aspects of life and work. It relies on advanced machine learning algorithms and, coupled with access to a vast database, enables the tool to generate highly sophisticated responses to almost any query (Božić, 2023). The generation of responses is made possible by utilizing over 175 billion parameters (Firat, 2023). The use of such a database allows the program to stand out due to its ability to understand and interact with users (Chenfei et al., 2023). A significant measure of this tool's success is its achievement of gaining a million users within just five days (Haque et al., 2022). One distinguishing feature of ChatGPT compared to other AI-based tools is its ability to perform specific tasks based on specific user instructions (Shujian et al., 2023). Through literature analysis, this tool finds wide application in radiology (Biwas, 2023), public health (Biwas, 2023), education (Firat, 2023), programming (Nigar et al., 2023), in-context learning (Ori et al., 2023), GPT-based intelligent systems (Zhent et al., 2023), and many other fields. ChatGPT was developed by the OpenAI research laboratory, which conducts research in the field of artificial intelligence. It was established in San Francisco to create friendly artificial intelligence for the benefit of humanity (Mhlanga, 2023).

METHODS

The methods used in the article are related to testing the potential implementation of ChatGPT as a tool to support inventory management in a manufacturing company. The article proposes two research hypotheses:

H1: *It is possible to integrate the ChatGPT tool with the inventory management system of a selected manufacturing company.*

H2: *ChatGPT can increase the accuracy of plans in the area of inventory* management.

The second hypothesis is further divided into two parts due to the variety of product ranges and order fulfillment periods:

H2.1: *ChatGPT can increase the accuracy of plans in the area of inventory management for products with a short ordering period.*

H2.2: *ChatGPT can increase the accuracy of plans in the area of inventory management for products with a long ordering period.*

The article also poses two research questions:

RQ1: *What functionalities must ChatGPT possess in order to be integrated into the operations of a manufacturing company?*

RQ2: *What parameters in the area of inventory management must be characterized in order to use ChatGPT?*

In addition to testing ChatGPT, the authors also decided to include results from a predictive algorithm created for the study. This allowed for a comparison of the forecasting results of ChatGPT with both human decisions and results obtained using the algorithm. The authors decided to compare the three solutions connected with assortment management. The first case concerns the current situation in the case study being tested, where supply is based on supply worker decisions. The other two is the authors' proposition of using a simple forecasting algorithm based on *auto.arima()* in the R programming language (2nd case) and with the use of ChatGPT (3rd case).

The assortment examined here consists of parts that are necessary to build a fully functional water dispenser. Out of several thousand elements, three positions were selected that are of the highest importance to the company, with a division based on the delivery lead time from the suppliers. The selection of positions was made after consultation with managers involved in the company's procurement process. The absence of any of these positions is unacceptable as they are integral components of every device manufactured by the company, which would result in a halt in the production process and a suspension of shipments of finished products to customers. The delivery lead time for a particular position is determined by the location of the supplying company, material availability, complexity of production, and the time required to fulfill the order. Due to the company's confidentiality, all positions have been assigned new codes, where the first character represents the number of days needed to fulfill the delivery, and the last character represents the identifier of the position. Positions with a one-week lead time come from local suppliers and have a low level of complexity. Positions with a two-week lead time also come from local suppliers but have a slightly higher level of complexity. Positions with a three-week lead time come from neighboring countries and represent a high level of complexity. Positions with a 12-week lead time are transported from Asia to Poland using trains. These are the elements that, compared to other positions, may sometimes have issues with material availability for production. The two cases considered here were tested based on the logic shown in Figure 1.

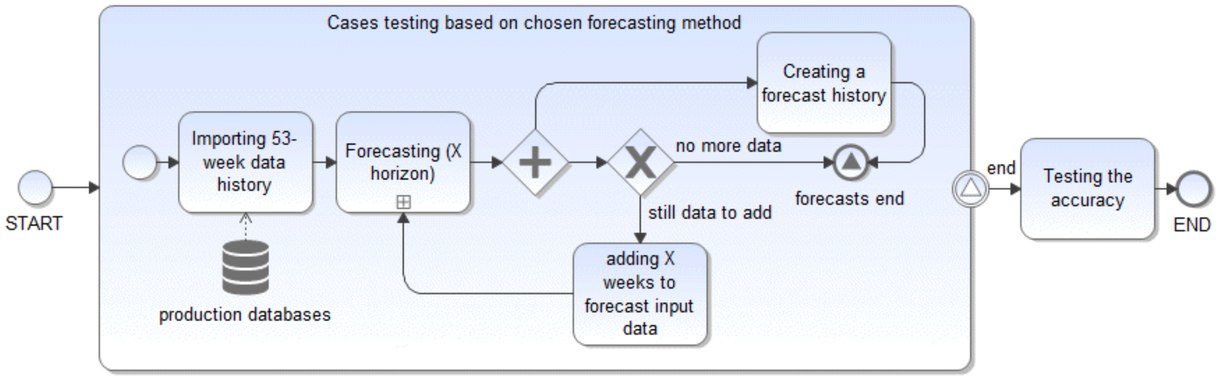

Fig. 1. Workflow of accuracy testing process. Source: Authors' own work.

The initial data for the analysis related to 53 weeks from 2020, and the data on which the results were tested comes from mid-2021. Forecasts were made in weekly granulation. The forecast horizon (X in the figure) was the time needed to complete the order and matched the periods of updating the forecasting tools with new data. There are four groups of products in the company, broken down by waiting for the order, hence X was 1,2,3or 12. For each of the groups, the 3 most important materials ordered by the company were selected. Thus, the cases that were discussed concerned the verifiability of forecasts for 12 products. The particular forecasting method approaches are explained below.

First case - supply based on demand forecasting tool

In this case, a tool based on a modified ARIMA (Autoregressive Integrated Moving Average) algorithm was proposed to control the supply system. ARIMA is a time series forecasting model that is commonly used in statistical analysis to understand the pattern of data over time and forecast future values based on the patterns found. ARIMA models can be used to model and forecast data that has three key characteristics: stationarity, autocorrelation, and seasonality. Stationarity refers to the property of a time series that has a constant mean and variance over time. Autocorrelation refers to the property of a time series, where the values of the series at different time points are correlated with each other. Seasonality refers to the property of a time series that shows regular patterns or cycles over a fixed period of time, such as daily, weekly, or monthly (Hyndman and Athanasopoulos, 2018).The ARIMA model is built by combining the AR (Autoregressive) model, the MA (Moving Average) model, and the differencing method. The AR component models the dependence of the current value on past values of the same series, while the MA component models the dependence of the current value on past errors. The differencing method is used to remove the trend and seasonality of the series, making it stationary and easier to model (Box et al., 2015). ARIMA models are commonly used in demand forecasting because they are able to capture the complex patterns and trends often found in demand data, such as seasonality and autocorrelation. The tool presented in the following paper returns the best ARIMA model, according to either AIC, AICc or BIC values. The function conducts a search for a possible model within the order constraints provided. The algorithm chosen is provided by *library(forecasts)* at R programming language and it is called *auto.arima()*, so the forecasts were calculated in the following parameters:

forecast <- auto.arima(DATA, lambda = "auto", biasadj = TRUE)

The whole script which was used for forecasts calculation is available at the appendix (Appendix 1).

The use of the auto.arima() function was motivated by the fact that currently in demand forecasting, ARIMA-based algorithms are among the most commonly used for predicting demand. It is often the case that ML-(machine learning) supported algorithms are also algorithms related to the one presented. In the later part of the article, the terms ARIMA, auto.arima, and Aarima are used interchangeably to describe the presented algorithm.

Second case - demand forecasting based on ChatGPT

The forecast was generated using Chat GPT. The forecasting process was carried out in two stages. The first stage involved ChatGPT generating a template, which enabled further forecasting. This was made possible by making the query "Generate a template that will allow you to make a forecast of material consumption." In response, Chat GPT generated the following template that needs to be filled in.

- Forecast period (weeks, months, quarters, etc.):
- Type of production downturns (quantitative, qualitative):
- Time range for which historical data is available:
- Observation frequency (daily, weekly, monthly, quarterly):
- Historical data (please attach data in the appropriate format, e.g., spreadsheet):
- Factors that may affect the variability of production downturns (e.g., weather, seasonality, holidays, etc.):
- Forecast objective (production planning, human resource management, etc.):
- Any other information that may impact on the forecast (e.g., changes in the production process, changes in the company's strategy, etc.)
- The second step was to send ChatGPT the completed form for each item.
- Forecast period (weeks, months, quarters, etc): **Weeks;**
- Type of production downturns (quantitative, qualitative): **Quantitative;**
- Time range for which historical data is available: **53 weeks (for the initial inquiry.**

For each subsequent inquiry, this value was increased by the delivery time);

- Observation frequency (daily, weekly, monthly, quarterly): **Weekly;**
- Historical data (please provide data in the appropriate format, e.g., spreadsheet):

Historical demand for individual items has been implemented as the data;

- Factors that may affect the variability of production downturns (e.g., weather, seasonality, holidays, etc.): **Seasonality and weather;**
- Forecast objective (production planning, human resource management, etc.):

Production planning;

- Other information that may impact on the forecast (e.g., changes in the production process, changes in the company's strategy, etc.): **None.**

As an additional element, a request was added to provide a forecast in the form of a table for the next 26 weeks.

To evaluate the forecast accuracy, indicators such as MAPE, RMSE and MAE were used.

The authors are aware that these are not the only methods for measuring the accuracy of forecasts. Among other measurement methods, one can mention the Janus coefficient (Anderson, 2012) or the regression coefficient (Maciejowska et al., 2016). The authors chose to use the aforementioned indicators considering that these are measures frequently used both in practice and by researchers in publications describing the issues of verifiability and accuracy of forecasts (this is discussed, for instance, in the works of Chicco et al. (2021); Zhou et al. (2018); and Ostertagova and Ostertag (2012)). The authors are also aware of the issue associated with the correct selection of an indicator for forecast assessment and the problems and risks of choosing only one indicator for verifiability assessment. Therefore, in the subsequent analysis, they decided to test various indicators and, based on a weighted assessment, select the best forecast. The use of weighted assessment for the final verifiability evaluation is mentioned, among others, in the works of Kramarz and Kmiecik (2022), Sohrabpour et al. (2021), and Qi et al. (2014). The authors calculated the MAPE, RMSE, and MAE indicators using standard formulas.

Mean absolute percentage error (MAPE) is defined by the formula (Jeżyk and Tomczewski, 2014):

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{y_i - y_p}{y_i}\right|$$

where:
y_p – represents the predicted value;
y_i – represents the actual value;
n – represents the number of periods.

The root mean squared error (RMSE) is defined by the formula (Hodson, 2022):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - y_p)^2}$$

where:
n – represents the number of periods;
y_p – represents the predicted value;
y_i – represents the actual value.

The mean absolute error (MAE) is defined by the formula (Chai, 2014):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - y_p|$$

where:
n – represents the number of periods;
y_p – represents the predicted value;
y_i – represents the actual value.

RESULTS

In this study, two forecasting models generated by ChatGPT and an ARIMA-based algorithm were compared. Performance evaluation of the forecasts was done using indicators such as MAPE, RMSE, and MAE. Figure 2 presents a comparison of forecast results by ChatGPT and ARIMA based on the MAPE indicator.

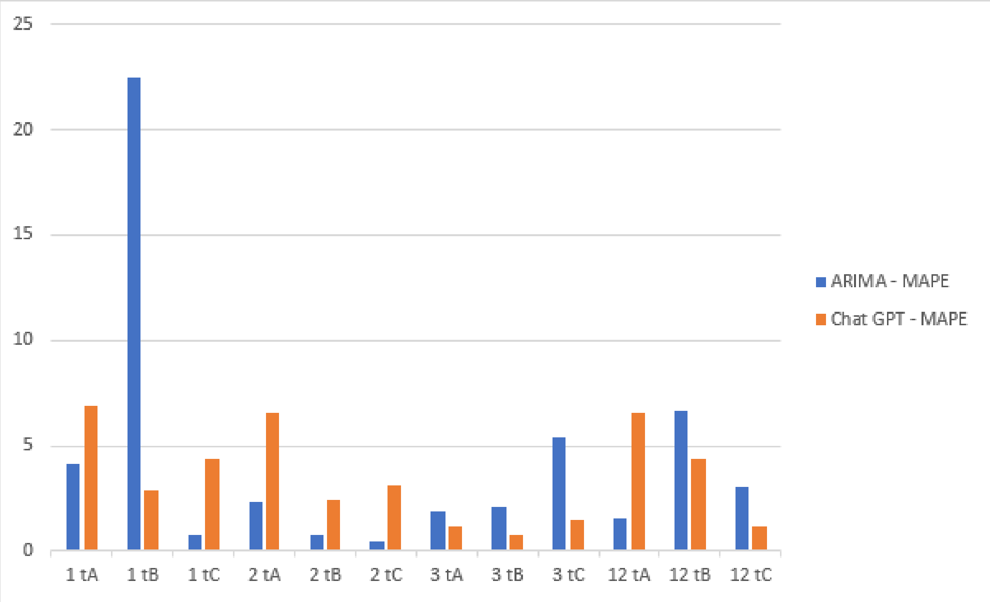

Fig. 2. Comparison of forecast results generated by ChatGPT and ARIMA based on the MAPE indicator. Source: Authors' own analysis based on data from the company.

By evaluating the forecast performance using the MAPE indicator, which measures the deviations of forecasts from actual values, it was assumed that lower MAPE values indicate smaller forecasting errors and greater accuracy of the model's predictions (Tofallis, 2013). The analysis of the results revealed that the forecasts generated by ARIMA were more accurate compared to ChatGPT for 6 references: 1 tA, 1 tC, 2 tA, 2 tB, 2 tC, and 12 tA. On the other hand, the forecasts generated by ChatGPT were more accurate for 6 references: 1 tB, 3 tA, 3 tB, 3 tC, 12 tB, and 12 tC. Analyzing Figure 2, a significant disparity can be observed between the two forecast models for each reference. Through analysis, it can be inferred that ARIMA made more accurate forecasts for references with a short LT (1-2 weeks). Meanwhile, ChatGPT proved to be more precise for references with a longer LT exceeding 3 weeks. Figure 3 presents a comparison of forecast results generated by ChatGPT and ARIMA based on the MAPE indicator.

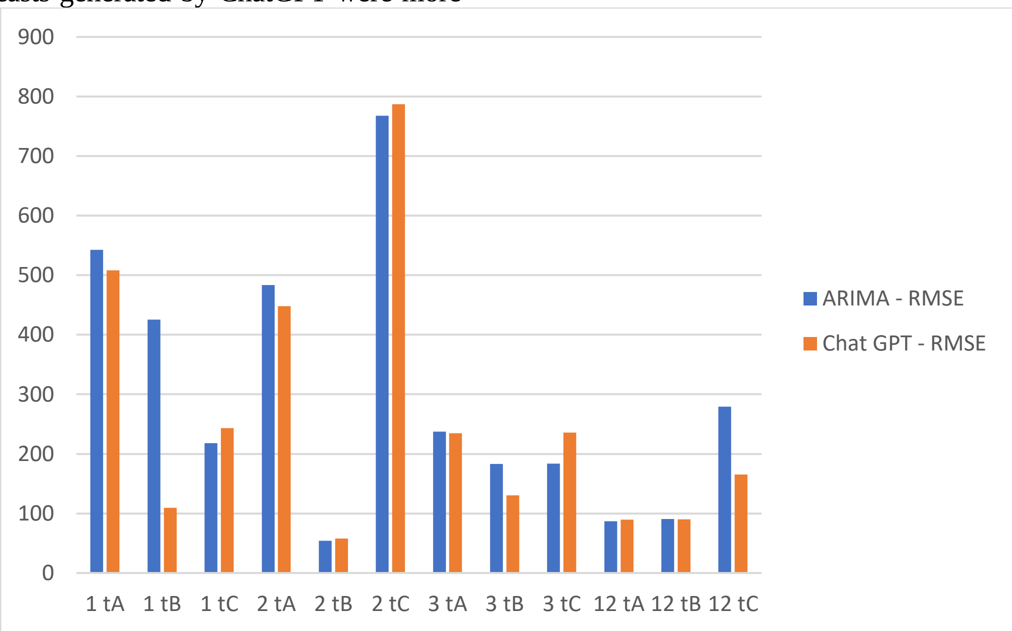

Fig. 3. Comparison of forecast results generated by ChatGPT and ARIMA based on the RMSE indicator. Source: Authors' own analysis based on data from the company.

The effectiveness of the forecast models was analyzed using the RMSE indicator, which measures the average squared error between the forecasted values and the actual data. Utilizing the RMSE indicator, smaller values indicate smaller deviations of forecasts from reality and greater accuracy of the predictive model (Botchkarev, 2018). The forecasts generated by ARIMA were more precise for the references: 1 tC, 2 tB, 2 tC, 3 tC. On the other hand, the forecasts generated by ChatGPT were more precise for the references: 1 tA, 1 tB, 2 tA, 3 tB, and 12 tC. References that obtained very close RMSE values for both forecasts are: 3 tA, 12 tA, 12 tB. Based on this analysis, it can be inferred that the forecast model generated by ARIMA is more accurate for positions with an LT of 2 weeks, while ChatGPT produced a forecast that achieved better results in terms of the RMSE indicator for positions with an LT of 1 week. Figure 4 presents a comparison of forecast results generated by ChatGPT and ARIMA based on the MAE indicator.

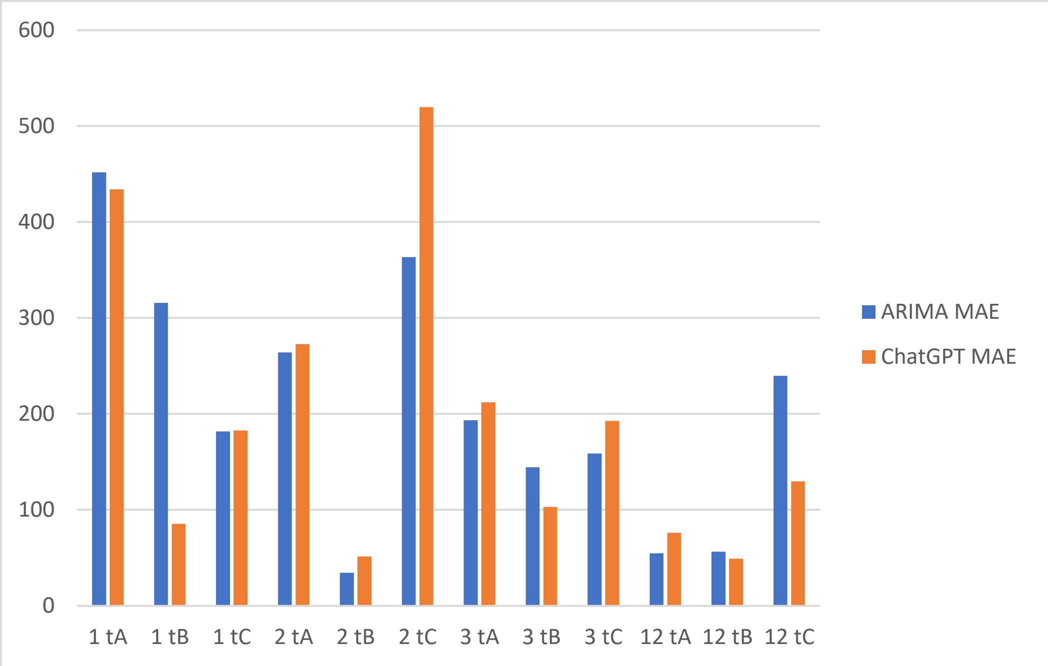

Fig. 4. Comparison of forecast results generated by ChatGPT and ARIMA based on the MAE indicator. Source: Authors' own analysis based on data from the company.

Another analysis of the forecast models' effectiveness was based on the MAE indicator, which measures the average absolute error between the forecasted values and the actual data. The smaller the value, the smaller the forecasting errors and the greater the accuracy of the predictive model (Robeson, Willmott, 2023). This analysis revealed that the forecast model generated by ARIMA achieved better results compared to ChatGPT for references such as 2 tA, 2 tB, 2 tC, 3 tA, 3 tC, 12 tA. On the other hand, ChatGPT proved to be more effective for references 1 tA, 1 tB, 3 tB, 12 tB, and 12 tC. The reference that obtained very close RMSE values for both forecasts was 1 tC. Based on this data, it can be inferred that the forecast generated by ARIMA was more accurate primarily for positions with an LT higher than 2 weeks, while ChatGPT proved to be more precise for positions with an LT of approximately one week. The final evaluation of ChatGPT's performance and the ARIMA-based algorithm is presented in Table 1. The weights and comparison intervals were consulted with managers responsible for assortment management and procurement operations.

Table 1. Final assessment for the analyzed cases.

		Total result (A)	Weight (B)	Final result (A * B)	Solution final score (C)
ChatGPT	MAPE	7.5	0.4	3	7.3
	RMSE	8	0.2	1.6	
	MAE	7.5	0.2	1.5	
	Number of better results	6	0.2	1.2	
Aarima	MAPE	6	0.4	2.4	5.8
	RMSE	4	0.2	0.8	
	MAE	7	0.2	1.4	
	Number of better results	6	0.2	1.2	

Source: Authors' own analysis based on data from the company.

The evaluation of references was based on intervals developed by the company that agreed to provide data for research purposes. For each reference, MAPE, RMSE, and MAE indicators were calculated using a specific forecasting model. The comparison of forecasts based on the analysis of these indicators allowed values to be identified that represent the absolute difference between the specific indicator results for a given reference, presented as a percentage of the highest absolute difference value. For each reference, unified intervals were adopted based on different indicators, as utilized by the company according to the following logic:

- 0.5 if the percentage of the absolute difference for a specific indicator falls within the range of 0-5% for a given reference;
- 1 if the percentage of the absolute difference for a specific indicator falls within the range of 5%-40% for a given reference;
- 2 if the percentage of the absolute difference for a specific indicator falls within the range of 40%-80% for a given reference;
- 3 if the percentage of the absolute difference for a specific indicator falls within the range of 80%-100% for a given reference.

The results were summed for each forecast accuracy indicator (column A), and then the results were multiplied by specified weights. The determination of weights for different indicators has been previously presented by Kramarz and Kmiecik (2022), among other researchers. In this article, the authors arbitrarily assigned the following weights: MAPE - 0.4; RMSE - 0.2; MAE - 0.2, and the number of better results - 0.2. This provided the basis for calculating the weighted assessment and determining the final evaluation of the two proposed tools (column C). Based on the above steps, it was concluded that in the case examined here, ChatGPT is a better solution for forecasting than Aarima (ChatGPT score - 7.3; Aarima score - 5.8).

DISCUSSION

Forecasting is an incredibly important element of decision-making processes. Errors in forecasting can lead to significant losses. Underestimation results in potential profit loss, while overestimation increases the costs for the company (Duda, 2017). One of the key areas that can be utilized in forecasting is product sales (Duda, 2016). The present study focuses on evaluating the accuracy of forecasts generated by ChatGPT and ARIMA. In this article, ChatGPT achieved better reliability in terms of the generated forecasts compared to the algorithm it was compared with. This provides a basis to explore the potential use of ChatGPT as a tool for forecasting demand in a manufacturing company. Due to its forecasting capabilities, this tool can support the assortment management system conducted within the company.

The use of the auto.arima() algorithm has many advantages. The ARIMA-based model is a model that is one of the most commonly used models for forecasting demand in business operations (Fattah et al., 2018). Using this algorithm and modifications to it provides a wide range of possibilities in assortment management supported by forecasting. On the other hand, ChatGPT is a relatively new tool that also enables forecasting, as observed in stock price movement forecasting (Lopez-Lira and Tang, 2023), forecasting the effects of global warming (Biswas, 2023), and forecasting activity in the textile industry (Rathore, 2023). However, forecasting demand or other variables is an ongoing development. Based on the research conducted and the case study mentioned previously, it can be stated that ChatGPT can be used in a company to forecast the demand for products ordered by a manufacturing company. The ChatGPT forecasting algorithm operates correctly and provides relatively good results when compared to those obtained using auto.arima. However, integrating the ChatGPT tool with the systems currently used in the company can be problematic. H1 was verified negatively, as the tested ChatGPT tool in its basic form is difficult to implement in business operations. This is due to the fact that data operations (such as import and export) are limited in terms of the number of characters manually entered by the user or generated by the tool. One potential solution could be to implement the GPT language itself as a plugin for the ERP software currently used in the company (Chen et al., 2023). H2 was verified positively, as ChatGPT can improve the accuracy of plans in assortment management both in short- and long-term order fulfillment. ChatGPT demonstrated better reliability in forecasting compared to the standard ARIMA-based forecasting tool. In order to integrate ChatGPT into business operations, it would need to demonstrate the ability to integrate and utilize the GPT language model as a plugin for the currently employed solution. Full integration between the ERP system used in the company and the GPT language is necessary to ensure smoothness and efficiency in the forecasting process. In ChatGPT, appropriate prompts can also be specified to automate the process of requesting a forecast. However, a significant issue for long-term use of ChatGPT is the fact that most machine learning models degrade over time (Vela et al., 2022), thus there is a risk of decreased reliability of forecasts in the longer term. Additionally, the use of such solutions often raises questions regarding copyright, data processing security, and confidentiality when utilizing such solutions for sharing a company's know-how (Oviedo-Trespalacios et al., 2023). This risk, along with the lack of standardization in the utilization of large language models based on machine learning and artificial intelligence, can lead to opportunism in the implementation and use of such solutions by businesses.

CONCLUSIONS

From the research on generating forecasts using ChatGPT, several important conclusions regarding this tool can be observed. Firstly, it is not possible to attach any data files to the conversation with ChatGPT, which means that all data must be manually copied and pasted. This method can be time-consuming, especially when generating forecasts for a large number of references. Another issue is the possibility of interruption during the generation of a forecast at random moments. In such cases, it is necessary to resend the completed form, resulting in an extended time dedicated to the forecast generation process.

Another important aspect is the format of the forecasts generated by ChatGPT, which is presented in textual form. Transferring data from the OpenAI platform to a program for further analysis may require additional operations. This entails additional effort and potential risks of errors when transferring the data.

In summary, despite certain limitations and inconveniences associated with using ChatGPT for generating forecasts, the tool has demonstrated higher accuracy compared to auto.arima in estimating production outputs. However, further investigation and refinement of the forecast generation process using ChatGPT are necessary to optimize the time and efficiency of this tool.

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APPENDIX

Appendix 1: Forecasting script for auto.arima() for the items with 12 weeks of forecasts horizon and 12 weeks of data updating.

```
library(readxl)
data <- read_excel("data_file_path") #import of data from .xlsx
data$quantity <- abs(data$quantity) # change the quantities to absolute value
X <- 12 #setting the forecasts horizion and update period for forecasts X = OR(1;2;3;12)
library(forecast)
forecast <- auto.arima(data[1:53, "quantity"], lambda = "auto", biasadj = TRUE) #forecasts by using
an auto.arima() function
forecast_sheet <- data.frame(Forecast = forecast(forecast, h = X)$mean * -1) #first forecasts
write.xlsx(forecast_sheet, "output_path")
# Creation and update condition based on X parameter
if(X == 12) {
  update <- 3
} else if(X == 3) {
  update <- 9
} else if(X == 2) {
  update <- 13
} else if(X == 1) {
  update <- 26
}
# Data update and creation of next Excel sheets with forecasts
for(i in 1:update) {
  data <- rbind(data, data[nrow(data), ])
  forecast <- auto.arima(data[(nrow(data)-52):nrow(data), "quantity"], lambda = "auto", biasadj =
TRUE)
  forecast_sheet <- data.frame(Forecast = forecast(forecast, h = X)$mean * -1)
  write.xlsx(forecast_sheet, paste0("output_path", i+1, ".xlsx"))
}
forecast_sheet$Forecast <- forecast_sheet$Forecast* -1
library(openxlsx)
output_sheet <- createWorkbook()
for(i in 1:(update+1)) {
  sheet <- read.xlsx(paste0("output_path", i, ".xlsx"), sheet = 1)
  addWorksheet(output_sheet, sheetName = paste0("Arkusz ", i))
  writeData(output_sheet, sheet = i, x = arkusz)
}
saveWorkbook(output_sheet, "output_path")
```

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ORIGINAL PAPER

A MODEL FOR INVENTORY MANAGEMENT AND WAREHOUSE PERFORMANCE IN THE SOUTH AFRICAN RETAIL INDUSTRY

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ABSTRACT. Background: The South African retail sector faces numerous inventory management-related problems that have detrimental effects on both inventory and warehouse performance. Some of the negative effects include the inability to fulfil orders, poor-quality control and inventory management operating systems, and ineffective warehouse security and layout design. It is necessary to develop and identify interventions for mitigating these problems. Additionally, literature on inventory and warehouse management in the South African retail sector is currently limited. The study tests a model for linking inventory management to warehouse performance in the retail industry in South Africa.
Method: The study used a quantitative survey method involving 203 supply chain professionals selected from retail outlets in the Gauteng and KwaZulu Natal provinces. Data were analysed using structural equation modelling based on the partial least squares technique.
Results: Three inventory management practices: inventory investment and ABC analysis contributed positively to inventory performance. Inventory performance contributed positively to warehouse performance.
Conclusions: Inventory management and performance are important drivers of warehouse performance in the retail sector. However, a correct mix of inventory management practices is essential. The study offers several contributions. Theoretically, the study provides insights into the contribution of inventory management to warehouse performance in retail environments. Specifically, the study identifies the inventory management practices that are important in optimising both inventory and warehouse performance in retail supply chains.

Keywords: Inventory management practices; inventory performance; warehouse performance; South African retail industry

INTRODUCTION

South Africa, which is the most industrialised country in Africa, boasts of some of the largest retail outlets on the continent. Growth in the retail sphere of South Africa has increased exponentially over the years and is witnessed through the ever-increasing number of shopping malls and the upsurge of online marketing [Mafini and Dhurup 2015; Makhitha and Ngobeni 2021]. According to Frazer [2022], South African retail sector sales grew by R547 billion, which equates to 14% in 2022, compared to 2021. In 2022, the sector's gross domestic product (GDP) contribution increased steadily from 0.7% in the second quarter to 1.6% in the third quarter of the year [Statistics South Africa 2022]. This positive performance is bolstered by several factors, which include the surge in online purchasing activities, the diversification of operational processes, which has resulted in an increase in product offerings, as well as a customisation drive. These are all meant to optimise customer satisfaction [Goga, Paelo and Nyamwena 2019, PRNewswire 2023]. Also, the efforts of the South African government to boost the economy in the post-COVID-19 pandemic period helped to prop up critical economic sectors, including retail business [Rajagopaul, Magwentshu, and Kalidas 2020 Nazir 2021].

The recent boom in the South African retail sector has attracted several hindrances that

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threaten the viability and success of this supply chain. These challenges include the inability to fulfil orders and poor-quality control and inventory management operating systems, such as warehouse management systems [Mhuri 2020]. Malgas and Zondi [2020] point to how the sector's sloppy warehouse security and layout design hinder effective storage spacing, becoming major setbacks. Inaccurate lead times in the movement of goods between facilities, inefficient stock tracking and data availability, together with stock damages and theft are all commonplace in the retail sector [Barloworld Logistics 2021]. A few authors [Govind, Luke, and Pisa 2017, Cilliers 2018] have reported the retail sector's inability to cope with volatile demand results in high inventory levels due to inaccurate inventory counts and stockouts. Shozi [2021] noted the poor adoption of recent technologies as one of the major constraints affecting retail sector warehouse operations. Lastly, the COVID-19 pandemic hangover, the 2021 July unrest, and the shortage of electrical power in South Africa (load-shedding) have all worsened the operational capabilities and performance of retail firms [PropertyWheel 2020, Inglesi-Lotz and Ajmi 2021].

The present study aims to test a research model for linking inventory management to warehouse performance in the retail industry in South Africa. The specific objectives of the study include (1) assessing the impact of inventory management practices on inventory performance and (2) measuring the impact of inventory performance on warehouse performance. The study places its prime emphasis on a few inventory management practices, namely Inventory Shrinkage prevention (ISP), inventory investment, inventory turnover optimisation (ITO), inventory control, and ABC analysis. The study examines their individual effects on inventory performance as a catalyst for the improvement of warehouse operations. To address the challenges presented above, a possible solution would be to optimise the capacity and capability of the warehousing systems used in the retail supply chain. However, this may require well-functioning-inventory management systems that serve as a continuous feeder into the available warehouses as they provide the stock for storage. As suggested by Granillo-Macías [2020], inventory management must be strengthened due to its role in improving warehouse performance. The significance of inventory and its importance as an asset in the retailing sector is evident, as it signifies what the firm has to offer to its consumers, for example, goods for purchase; while substantial expenses are connected with inventory holding, the latter subsists within warehouses [Breivik 2019]. The present study is thus intended to investigate this profound relationship between inventory and warehouse management with a view to providing information that may be used to mitigate some of the challenges that are constraining these functions within the retail sector.

Some decent evidence of studies on inventory management within the South African retail sector exists [Eicker and Cilliers 2018, Mondo, Twum-Darko, Ansen and Tengeh 2022, Munyaka and Yadavalli 2022]. However, studies that focused on the specific impact of inventory management on warehouse performance in the same sector are rare to find. The current study addresses this research gap by evaluating the impact of inventory management on warehouse performance in the South African retailing sector. The results of this study could prove useful to the retailing sector by identifying the inventory management practices that are relevant to that supply chain in the context of devising approaches to improve the performance of warehousing facilities.

This article is structured as follows: the next section discusses the South African retail industry literature review and the study's constructs. The conceptual model and hypotheses development are addressed next. The research methodology, data analysis, and study results discussion are then presented. The article concludes with conclusive remarks and provides theoretical and managerial implications and limitations of the study.

LITERATURE REVIEW

South African retail industry

The South African retail sector is one of the fastest growing and contributing sectors in the economy. It contributed to about R365 353 million in trade sales between October and December 2022, which is a substantial increase compared to R342 571 in the same period in 2021 [Statistics South Africa 2022]. In terms of employment creation, the sector contributed a modest 2.6% of the total employment figures in the second quarter of 2022 despite the staggeringly high unemployment rate [Statistics South Africa 2022]. These socioeconomic indicators further highlight the role the sector plays as an active contributor to the economic growth and social development of the livelihoods of South Africans [Abraham 2022]. The growth of the retail sector may be attributed to the expansion of South Africa's retail companies to online platforms and markets outside South Africa [Mantandon 2013, Games 2020, Lomberg 2023]. For example, companies such as Shoprite and PicknPay have opened stores in neighbouring countries such as Botswana, Namibia, and Zimbabwe [Dakora and Mason 2016]. The South African trade space is dualistic, involving formal and informal sectors [Charman, Petersen, Piper, Liedeman, and Legg 2015]. Formal retail is regarded as highly tax regulated and is dominated by six major retailing giants, namely Shoprite Checkers, Woolworths, PicknPay, Massmart, and Spar. The informal retail sector exists within the margins of regulation and legality and is dominated by spaza shops, flea markets, and small-scale produce vendors [Charman et al. 2015, Stiehler-Moulder and Mahlape 2021].

The current study considered the formal retailing sector since it is the one with more established inventory and warehouse facilities found in South Africa.

Inventory management practices

Inventory management, also commonly known as stock management, refers to a set of processes for organising, managing, and making the products of a firm available to its customers [Achieng, Paul, and Mbura 2018]. Firms have a wide choice of inventory management practices from which to select. Examples include inventory control, process auditing stock valuation, inventory shrinkage (preventive), inventory investment, inventory turnover, and ABC analysis [Oballah, Waiganjo, and Wachiuri, 2015, Hussein and Makori 2018]. The six inventory management practices being considered, namely inventory investment, shrinkage prevention (ISP), turnover optimisation (ITO), inventory control, and ABC Analysis (ABC), are important elements of inventory and warehouse management because they are central to the optimisation of internal controls for inventory management in the provision of value to customers [Opoku, Fiati, kaku, Ankomah, and Opoku-Agyemang 2020].

In addition, a study by Ekegbo, Quede, Mienahata, Siwangaza, Smit, and Bruwe [2018] argued that these practices are critical indicators of inventory performance.

Adopting preventive measures to minimise inventory shrinkage and turnover is important to sustaining inventory performance [Hussein and Makori 2018]. Several scholars [Wambua, Okibo, Nyang'Au, and Ondieki 2015, Breivik 2019] indicate that the use of ITO, inventory control, and the ABC analysis is an important yardstick for assessing inventory performance. Therefore, for the purposes of the current study, the selected inventory management practices are deemed relevant predicting factors that drive both inventory and warehouse performance in the retail sector.

Inventory shrinkage prevention

Inventory shrinkage is the loss of inventory due to various factors [Knego and Misevic 2016]. This loss of inventory may be attributed to various factors that include the theft of products by employees, shoplifting, vendor fraud, and errors in administration among others [Alleleyn 2016, Yu, Chen and Wang 2019]. Thus, ISP refers to preventive measures adopted by a firm to minimise or mitigate the loss of its inventory [Li, Song, Sun, and Zheng 2019]. According to Atnafu and Balda [2018], ISP is part of inventory management practice and can affect inventory performance if they are not well managed. Therefore, the literature supports that ISP can negatively and positively impact inventory performance depending on how they are integrated into the systems. Moreover, Choi, Rabinovich, and Richards [2019] established that ISP plays a vital role in improved performance and the competitiveness of the organisation.

Inventory investment

Inventory investment refers to a change in inventory and goods that are in the production process in the company over a specific time frame [Lee, Zhou, and Hsu 2015, Chod 2016]. It can also be described as a dimension of an organisation's change in inventory levels from one time to the next [Jim 2020]. Inventory investment contributes to the most significant part of current assets and working capital in most activities. Thus, it becomes important to have adequate control and inventory management [Dhere 2015]. Therefore, firms are encouraged to hold a larger inventory due to the likelihood of increased production volumes at lower costs, leading to injection into inventory investment [Kim 2020].

Inventory turnover optimisation

Inventory turnover refers to a company's cost of goods sold, divided by average inventory, with less profitable operations [Feng, McVay, and Skaife 2015]. It may also be defined as the rate at which stock is used, sold, and replenished [Amanda 2019]. Inventory turnover optimisation is the process of increasing and sustaining the rate at which inventory items are sold and efficiently replenished within the warehouse facilities of firms to ensure the satisfaction of customers [Lobo, Kumar, and Ravikumar 2013]. This can be achieved, for instance, by disposing of all stock that is not selling by reducing the price to increase its sale. Kwak [2019] stressed that inventory turnover is a critical tool as a performance measure. It is effective as it measures the movement of products to the customers. Lastly, the higher the inventory turnover, the more the cash flow decreases due to slow-moving products that are not sold. It can be said that inventory turnover's significance indicates how quickly inventory turns into receivables through sales [Sonko and Akinlabi 2020].

Inventory control

Inventory control is the process of coordinating, controlling, and ensuring the accessibility and availability of stock and the prevention of any loss or surplus in inventory [Borade and Sweeney 2015]. Asana, Radhitya, Widiartha, Santika, and Wiguna [2020] describe inventory control as the process of holding the correct inventory and reducing the costs of the inventory to a minimum. Effective inventory control is critical in every company because an ineffective inventory system can result in loss of customers and sales. More revenue can be generated if inventory is effectively managed, which could directly affect a company's performance [Mohamad, Suraidi, Rahman, and Durratun 2016].

ABC analysis

ABC analysis is an analytical tool used to compare demand values of items' inventory control systems based on the rule of 80-20, known as the Pareto principle [Mehdizadeh 2020]. Douissa and Jabeur [2020] describe it as a widespread inventory management technique designed to classify inventory items based on their weighted scores into three ordered categories: A, B, and C. Category A contains the most important items, category B includes the items that are neither important nor less important, and category C specifies the least important ones. ABC analysis aims to determine the items of material expenses that significantly affect the cost and, consequently, the operational management process for making decisions [Nuzhna, Tluchkevych, Semenyshena, Nahirska, and Sadovska 2019]. It eliminates the shortages of expired volume-based costing systems and provides more reliable information regarding the production costs, profitability, and decisions taken by management on each cost activity respectively [Fei, Namazi, and Isa 2017].

Inventory performance

Inventory performance relates to how organisations measure the effectiveness and competence of using and replenishing inventory [Elsayed and Wahba 2016]. Furthermore, it is known for measuring inventory usage effectiveness and replenishment [Ladhar, Lajili, and Babai 2015]. The significance of inventory management cannot be undervalued, especially for retail merchandising, due to the complexity of managing their assets, which influence inventory and firm performance [Alrjoub and Ahmad 2017]. Lastly, effective inventory performance is paramount in running a business, given the need to optimise inventory costs [Muchaendepi, Mbohwa, Hamandishe, and Kanyepe 2019]. Hence, inventory performance is a key factor in achieving competitive advantages.

Warehouse performance

Warehouse performance may be perceived as a measure of the optimal use of storage space, customer relations activity, quality level, asset usage, and costs [Liviu, Ana-Maria, and Emil 2009]. The role of warehouse performance in the retail industry is presented in this aspect and its importance in the adequate distribution of goods to different retailing outlets [Pyza, Jachimowski, Jacyna-Gołda, and Lewczuk 2017]. Hence, it is noted that warehouses are critical nodes in the supply chain, such that improving their performance is essential when avoiding unproductive bottlenecks in the supply chain [Ribino, Cossentino, Lodato, and Lopes 2018]. Overall, warehouse performance is critical in a firm's value chain because it affects customer satisfaction and market reaction efficiency [Caridade, Pereira, and Silva 2017].

Research Model and Hypotheses Development

The research model of the study is presented in Figure 1 and comprises five predictors, namely Inventory Shrinkage prevention, (ISP), inventory investment, inventory turnover optimisation (ITO), inventory control and ABC analysis, one mediator (inventory performance), and one outcome (warehouse performance).

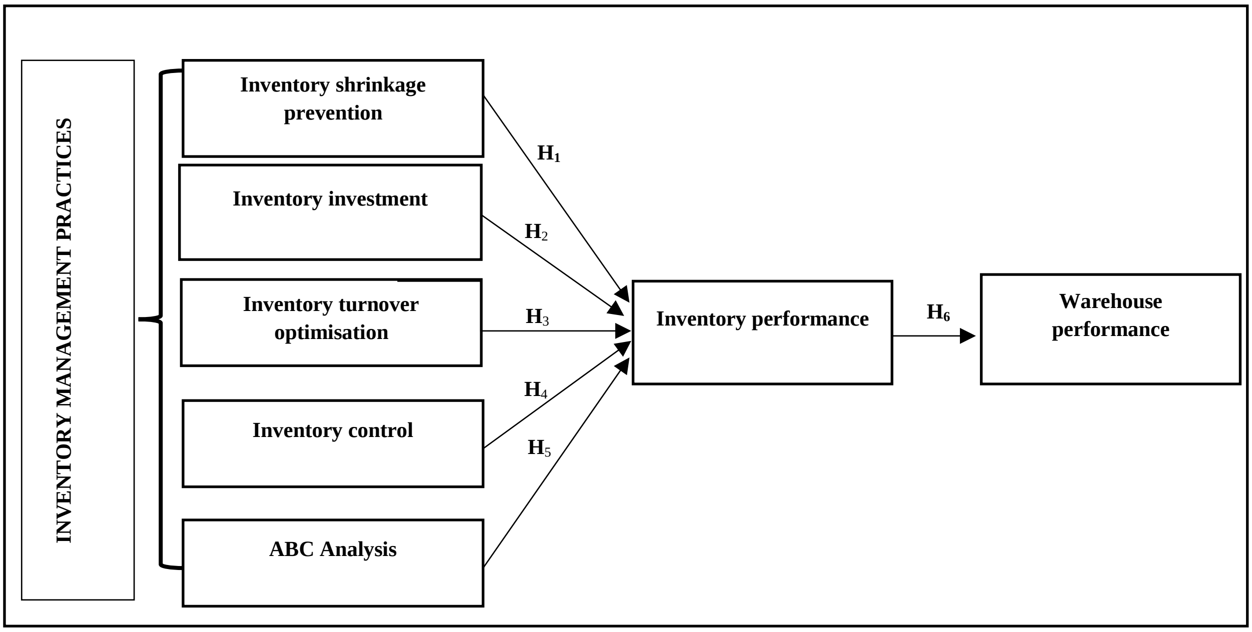

Fig. 1: Research Model. Source: Authors' own 559ptimization559tion.

Hypotheses Development

Inventory management practices and inventory performance

Several studies [Abimbola and Kolawole 2017, Mbah, Obiezekwem, and Okuoyibo 2019] confirm that ISP positively affects inventory performance in retail stores. A separate study by Akinlabi [2021] found a positive link between inventory investment and inventory performance. Evidence by Comez-Dolgan and Tanyeri [2015] suggests that ITO is a measure of inventory performance through its influence on the cost of goods sold to customers. Further research by Solis, Tavizon, and Alarcon [2020] shows that inventory control optimises inventory capacity. Also, Douissa and Jabeur [2020] assert that the successful implementation of ABC analysis indicates that the performance of each inventory item is measured, thereby reducing inventory costs. Another study by Mehdizadeh [2020] shows that the implementation of ABC analysis results in a significant improvement in inventory performance. These insights lead to the following hypotheses:

H_1: ISP positively affects inventory performance in the retail sector

H_2: Inventory investment positively affects inventory performance in the retail sector

H_3: ITO positively affects inventory performance in the retail sector

H_4: Inventory control positively affects inventory performance in the retail sector

H_5: Application of ABC analysis positively affects inventory performance in the retail sector

Inventory performance and warehouse performance

Analysing inventory and warehouse performance is critical for managers in evaluating the organisation's performance objectives and making sound decisions in value [Staudt, Alpan, Rodriguez, and Mascolo 2015]. Kritchanchai, Hoeur, and Engelseth [2017] found a positive relationship between inventory and warehouse performance. Recent research by Islam, Ali, Fathollahi-Fard, and Kabir [2021] indicates that inventory performance is an antecedent factor of warehouse performance. Additionally, Wang, Dang, and Nguyen [2020] found that a firm's inventory level strongly influences its warehouse performance. Therefore, the following hypothesis can be stated:

H_6: Inventory performance positively affects warehouse performance in the retail sector

MATERIALS AND METHODS

Research Design

The study was positivistic, following a deductive reasoning approach since the study was intended to test relationships between several research constructs. A quantitative survey design was followed to enable the generalisation of results to other retail environments.

Sampling Procedure

The final sample in this study consisted of 203 supply chain professionals drawn from the FMCG retail sector in the Gauteng and KwaZulu Natal provinces of South Africa. A selective sampling technique was employed to enlist respondents who were knowledgeable about SCM in the retail sector. To be included in the study, respondents were expected to possess at least two years of experience in any SCM role in the retail sector. Respondents were drawn from 70 branches of the major South African six retail firms. The final sample size of 203 respondents was considered adequate, based on the recommendation by Bentler and Chou [1987], who recommend five to 10 participants per each estimated parameter as the appropriate ratio number of respondents to the number of observed variables. This view finds support through Bollen [1989], who recommends that a ratio of three to five respondents should be the suitable determining parameter for structural equation modelling (SEM) studies. Additionally, Loehlin [1992] and Quintana and Maxwell [1999] recommend a minimum sample size of at least 200 or more as being suitable for multivariate studies using 10 to 15 measurement instruments. Therefore, the sample size of n=203 respondents applied in the current study satisfies the sample size recommendations cited above.

Measures and Fieldwork

Measurement scales used in the study consisted of 35 items that were adapted from previously validated scales. ISP was measured using a six-item scale adapted from Ekegbo et al. [2018]. In that study, the scale attained a Cronbach alpha (α) of 0.85. Inventory investment and inventory control were measured using five items, respectively, derived from Hussein and Makori [2018]; with scales of $\alpha=0.78$. ITO was measured using four items derived from Oballah et al. [2015]; with a scale of $\alpha=0.71$. ABC analysis used a four-item scale adapted from Wauna and Obwogi [2015], with a scale of $\alpha=0.71$. Inventory performance was measured using a five-item scale adapted from Awuah-Gyawu, Adzimah, and Brako [2015];

with α=0.83. Warehouse performance used a six-item scale adapted from Hussein and Makori [2018]; with α=0.88. Response options were presented on a five-point Likert scale anchored by 1= strongly disagree to 5= strongly disagree.

Data were collected using an online survey. Respondents accessed the online questionnaire through a link that was emailed to them. A submit button was provided, which transmitted the completed responses back to the principal researcher. The collection of data lasted for four months, between May and August 2022. Upon collecting and screening all received questionnaires, the final total number of questionnaires was n=203, which represents a response rate of 40.6.

Ethical Considerations

Ethics clearance was obtained from the Central Research Ethics Committee at a South African University of Technology. Permission to collect data was also obtained from each participating retail firm. The identities of respondents were not required during the survey, and respondents completed an informed consent form before participating in the study.

DATA ANALYSIS AND RESULTS

Once screened and finalised, the questionnaires were sorted into an Excel spreadsheet to perform the analysis. The Excel document was then exported to SPSS (Version 27.0) and Smart partial least squares (PLS version 3.0) platforms for data analyses. Hypotheses were tested using structural equation modelling (SEM) based on PLS.

Research Results

Sample profile

Regarding the gender distribution, male respondents (49.8%; n=166) were almost comparable to females (50.2%; n=167). A total of 11 (5.4%) of the respondents were holders of matric qualifications, while 87 (42.9%) possessed bachelor's degrees and 37 (18.2%) had completed postgraduate qualifications. I majority of respondents (n=64; 31%) had been employed for more than 10 yeIrs in the retail sector, followed by those possessing less than two years of experience (n=54; 26.6%) and groups with three to five years of experience (n=48; 23.6%), and those with six to nine years of experience being the least in number (n=37; 18.2%). The analysis also showed that 29.6 percent (n=60) of the respondents possessed at least 10 years of experience in the SCM profession, followed by the group with less than two years of SCM experience (n=56; 27.6%), and the final group possessing three to nine years of SCM (n=87; 42.9%). Most respondents (n=138; 68%) held positions such as general, warehouse, procurement, supply chain, distribution center, and inventory managers. Therefore the sample was considered to be representative since most categories in each demographic factor were included in the study and accurately represented the distribution of SCM professionals in the South African retail sector.

Exploratory factor analysis

Exploratory factor analysis (EFA) was used to assess the dimensionality of the measurement scales, based on the collected data. EFA is defined as an inter-correlation that occurs when there are many items in the questionnaire response and apportions the items into smaller groups known as factors [Hooper 2012]. Table 1 presents the EFA results, obtained through the Principal Components Technique based on Varimax Rotation. The Kaiser-Meyer Olkin ($KMO \geq 0.50$) test statistic and the Bartlett Test of Sphericity ($\chi 2 = 8105.213$; $p < 0.01$) were run to determine the factorability of the data. Despite all items loading well, only three garbage items, namely SHR_1, TUR_4, and WP_4, were discarded due to low factor loadings below the recommended minimum value of 0.5 [Peterson 2000].

A five-factor structure, explaining 77% of the variance, was extracted for the inventory management practices scale. The remaining 33% of the variance is explained by other inventory management practices that were not considered. The inventory performance scale was unidimensional, attaining 63% of the variance explained. Likewise, warehouse performance was also unidimensional, explaining 69% of the variance. Factor loadings for all items were higher than the minimum cut-off value of 0.5 and communalities were also higher than the minimum prescribed lower limit of 0.3 [Ferguson and Cox 1993]. The percentages of variances for all factor structures were higher than the 60% minimum threshold recommended by Lorenzo-Seva [2013].

Table 1. Exploratory factor analysis results

Construct code	Item codes	Communalities	Factor loadings	KMO Sampling adequacy	Bar'lett's Test of Sphericity	Eigenvalue	Percentage variance explained
ISP	SHR2	0.618	0.786	0.835	X^2=515.410 df=10 P=0.000	3.342	77.300%
	SHR3	0.609	0.780				
	SHR4	0.771	0.878				
	SHR5	0.628	0.793				
	SHR6	0.716	0.846				
INV	INV1	0.527	0.726			2.787	
	INV2	0.504	0.710				
	INV3	0.715	0.846				
	INV4	0.625	0.790				
	INV5	0.415	0.645				
ITO	TUR1	0.626	0.791			2.035	
	TUR2	0.737	0.859				
	TUR3	0.672	0.819				
ACC	ACC1	0.573	0.757			2.478	
	ACC2	0.602	0.776				
	ACC3	0.666	0.816				
	ACC4	0.637	0.798				
ABC	ABC1	0.574	0.758			3.092	
	ABC2	0.896	0.947				
	ABC3	0.898	0.947				
	ABC4	0.724	0.851				
IPER	IPER1	0.334	0.578	0.810	X^2=483.294 df=10 P=0.000	3.163	63.259
	IPER2	0.587	0.766				
	IPER3	0.772	0.879				
	IPER4	0.733	0.856				
	IPER5	0.737	0.859				
WPER	WPER1	0.688	.830	0.851	X^2=540.750 df=10 P=0.000	3.431	68.616
	WPER2	0.766	.875				
	WPER3	0.668	.817				
	WPER4	0.593	.770				
	WPER5	0.716	.846				

ISP = inventory shrinkage prevention, INV = inventory investment, ITO = inventory turn562ptimizationation, ACC = inventory control, ABC = ABC analysis, IPER = inventory performance WPER= warehouse performance

Source: Authors' own compilation.

Psychometric Properties of Measurement Scales

The psychometric properties of measurement scales were assessed to determine their accuracy in producing reliable and valid results. The results are presented in Table 2.

Scale reliability was tested using four indicators, namely Cronbach's alpha coefficient (α), composite reliability test (CR), Rho_A statistic, and item-to-total correlations. The minimum acceptable value for Cronbach's alpha, CR, and Rho_A statistic to confirm scale reliability is 0.7 [Bacon, Sauer, and Young 1995, Christmann and Van Aelst 2006]. The results indicated in Table 2 confirm that this requirement was met for the three indicators across all measurement scales, thereby confirming scale internal consistency reliability. Additionally, item-to-total correlation results were higher than the minimum prescribed value of 0.3 [Howard and Forehand 1962], which also confirms scale reliability.

Three forms of validity were ascertained in the study. Content validity was assured through a review of the questionnaire by a panel of academics who have extensive experience in SCM Research. In addition, a pilot study was conducted, involving 60 respondents to provide a preliminary assessment of the measurement scales. Feedback from the panel review of the questionnaire and the pilot study was used to adjust the questionnaire in several ways, such as reviewing its wording and length and replacing ambiguous questions with clearer statements.

Table 2. Psychometric properties analysis results

Research constructs	Item codes	Factor loadings	Cronbach Alpha α Value	Item-to-total correlation	Rho A	C.R. value	AVE value
ISP	SHR_2	0.779	0.867	0.661	0.828	0.86	0.67
	SHR_3	0.767		0.648			
	SHR_4	0.887		0.790			
	SHR_5	0.803		0.661			
	SHR_6	0.843		0.746			
INV	INV_1	0.657	0.788	0.569	0.857	0.80	0.55
	INV_2	0.636		0.556			
	INV_3	0.847		0.688			
	INV_4	0.816		0.607			
	INV_5	0.723		0.469			
ITO	TUR_1	0.663	0.754	0.546	0.852	0.76	0.66
	TUR_2	0.889		0.646			
	TUR_3	0.868		0.756			
ACC	ACC_1	0.706	0.795	0.567	0.864	0.79	0.61
	ACC_2	0.748		0.592			
	ACC_3	0.858		0.644			
	ACC_4	0.817		0.622			
ABC	ABC_1	0.817	0.902	0.618	0.929	0.90	0.77
	ABC_2	0.930		0.895			
	ABC_3	0.924		0.899			
	ABC_4	0.825		0.742			
IPER	$IPER_1$	0.614	0.839	0.436	0.894	0.85	0.63
	$IPER_2$	0.745		0.637			
	$IPER_3$	0.859		0.777			
	$IPER_4$	0.864		0.726			
	$IPER_5$	0.859		0.725			
WPER	$WPER_1$	0.829	0.881	0.724	0.916	0.88	0.69
	$WPER_2$	0.881		0.794			
	$WPER_3$	0.801		0.711			
	$WPER_5$	0.777		0.648			
	$WPER_6$	0.848		0.739			

ISP = inventory shrinkage prevention, INV = inventory investment, ITO = inventory turnover optimisation, ACC = inventory control, ABC = ABC analysis, IPER = inventory performance WPER= warehouse performance

Source: Authors' own compilation.

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Three forms of validity were ascertained in the study. Content validity was assured through a review of the questionnaire by a panel of academics who have extensive experience in

SCM Research. In addition, a pilot study was conducted, involving 60 respondents to provide a preliminary assessment of the measurement scales. Feedback from the panel review of the questionnaire and the pilot study was used to adjust the questionnaire in several ways such as reviewing its wording and length and replacing ambiguous questions with clearer statements.

The study also tested for convergent validity, in this instance using two indicators, namely factor loadings and the average Average Variance Extracted (AVE). To confirm convergent validity, a minimum value of 0.5 is required for all factor loadings [Anderson and Gerbing 1988]. Moreover, a 0.4 minimum AVE score is required for each scale [Browne and Cudeck 1992]. As revealed in Table 2, these parameters were also satisfied in the current study, which confirms that scale items were converging on their corresponding latent variables. However, one item (WPER4) was discarded because it attained a factor loading of 0.345, which is below the recommended 0.5 lower limit.

The final form of validity that was tested in the study is discriminant validity. According to the Fornel Lacker Criterion, discriminant validity is said to be sufficient if the square root of the AVE for each construct is higher than its correlations with other constructs [Fornell and Larcker 1981]. The results of the discriminant validity tests are indicated in Table 3.

Table 3. Discriminant validity

Research Construct	Construction Correlation						
	ABC	ACC	INV	IPER	ISP	ITO	WPER
ABC	0.876**						
ACC	0.333**	0.784**					
INV	0.660**	0.326**	0.740**				
IPER	0.385**	0.353**	0.391**	0.794**			
ISP	0.446**	0.335**	0.506**	0.265**	0.817**		
ITO	0.209**	0.375**	0.328**	0.261**	0.193**	0.813**	
WPER	0.503**	0.348**	0.476**	0.598**	0.318**	0.329**	0.828**
** Correlation is significant at the 0.01 level (2-tailed); ISP = inventory shrinkage prevention, INV = inventory investment, ITO = inventory turnover optimisation, ACC = inventory control, ABC = ABC analysis, IPER = inventory performance WPER= warehouse performance own							

Source: Authors' own compilation.

As indicated in Table 3, all square roots of the AVE values were higher than the correlations for each construct, which confirms that there were no associations between items and constructs that were expected to be unrelated in this study.

Model Fit Assessment

In the current study, model fit was tested using the Standardised Root Mean Square Residual (SRMR) and the Normed Fit Index (NFI) as recommended by Shi, Maydeu-Olivares, and Rosseel [2019]. The results are presented in Table 4.

Table 4. Model Fit

Model Fit indices	SRMR	NFI
Acceptable threshold values	< 0.10	Between 0 and 1 (NFI value to be closer to 1)
Sources	Petrowski, Kliem, Sadler, Meuret, Ritz, and Brahler [2018]	Schuberth, Henseler, and Dijkstra [2018]
Results obtained	0.097	0.713 (0.7)
Decision	Supported	Supported
Note: SRMR = Standardised Root Mean Square Residual; NFI= Norm Fit Index.		

Source: Authors' own compilation.

The results in Table 4 indicate an SRMR value of 0.097 and an NFI score of =0.713, both of which align with the prescribed thresholds. Hence, the data used in the final analysis were able to fit the model.

Path Analysis Results

In using PLS-SEM, the actual hypothesised relationships are tested using a technique known as path analysis. Path analysis refers to an assessment of the strengths and effects of the relationship between a set of observed constructs [Lleras 2005]. The results are presented in a graphic structural model derived from the SMART PLS platform. The resultant model for the current study is presented in Figure 2.

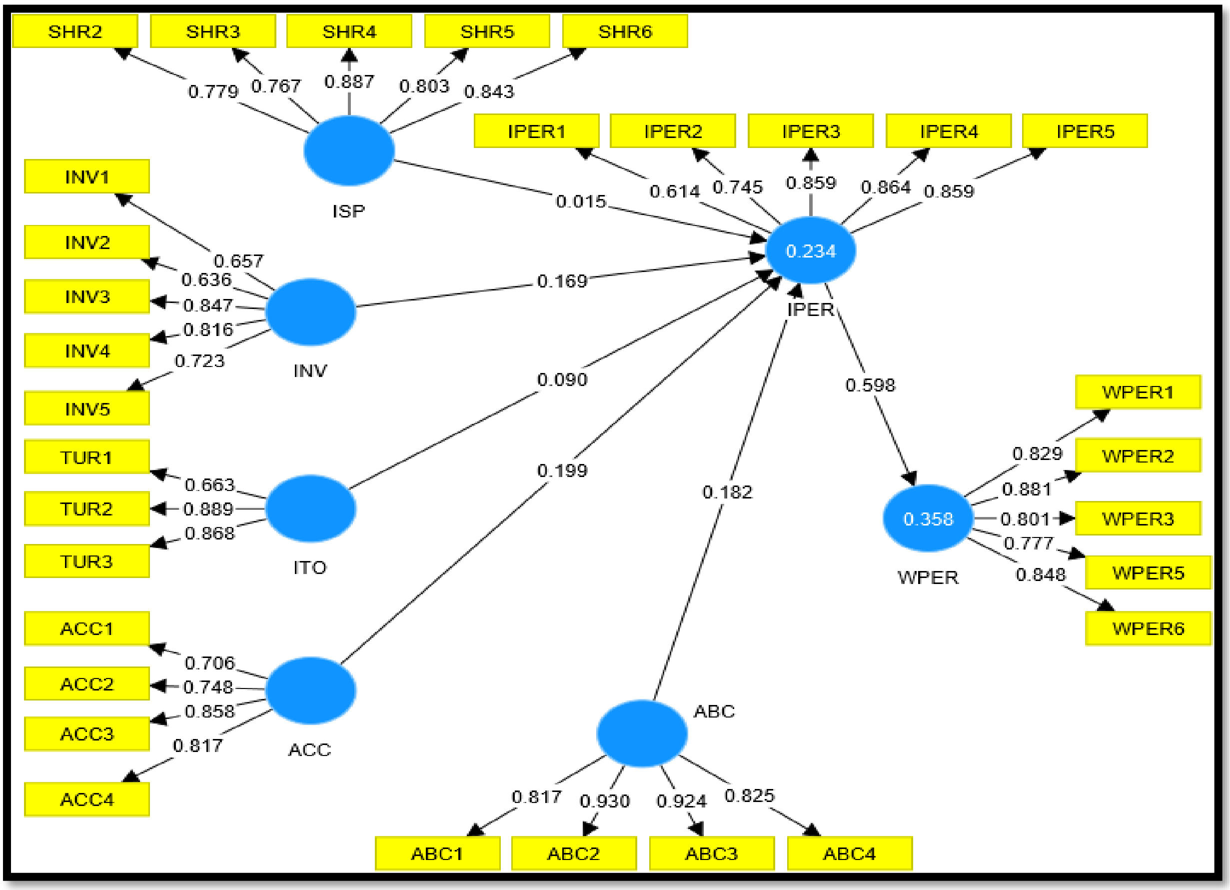

Fig.2. Structural model results. Source: Authors' own computation.

In Figure 2, each oval shape represents a research construct (latent variables), while the rectangles represent the scale items (observed variables). The scores placed in the arrows connecting the latent and observed variables are the factor loadings. The values placed between the latent variables are the path coefficients indicating the magnitude of the hypothesised relationships. The scores placed within IPER and WPER are the r^2 values. An r^2 score of 0.234 within IPER demonstrates that the five inventory management practices considered in the current study contribute to 23.4% of the variance in inventory performance. Likewise, the 0.358 r^2 score within WPER illustrates that inventory performance as measured in the present study contributes to 35.8% of warehouse performance. Overall, other factors were not included in the present study, which also contributes to the remaining variance in both inventory and warehouse performance. The results of the hypotheses tests are summarised in Table 5.

Table 5: Results of structural equation model analysis

Suggested path	Hypothesis	Path coefficients β	T statistics	P values	Decision
ISP → IPER	H_1	0.015	0.192	0.848	Rejected
INV → IPER	H_2	0.169	2.027	0.043	Supported
ITO→ IPER	H_3	0.090	1.414	0.158	Rejected
ACC → IPER	H_4	0.199	2.457	0.014	Supported
ABC → IPER	H_5	0.182	2.060	0.040	Supported
IPER→ WPER	H_6	0.598	12.307	0.000	Supported

Significance level <0.05; * significance level <0.01; *** significance level <0.001**
ISP=inventory shrinkage prevention; INV=inventory investment; ITO=inventory turnover optimisation; ACC=inventory control; ABC=ABC analysis; IPER=inventory performance; WPER=warehouse performance

Source: Authors' own compilation.

Table 5 shows that H2: Inventory investment and inventory performance (β=0.169), H4: Inventory control and inventory performance (β=0.199), H5: ABC and inventory performance (β=0.182) and H6: inventory performance and warehouse performance (β=0.598) were supported and accepted. However, H1: ISP (β=0.015) and H3: ITO and inventory performance (β= 0.090) exerted no influence on inventory performance. Therefore, these hypotheses were rejected.

DISCUSSION OF RESULTS

Inventory Management Practices and Performance

Three inventory management practices exerted a positive influence on inventory performance. The first of these is inventory investment (β = 0.169; t = 2.027; p = 0.043), the result of which demonstrates that it predicts inventory performance in the retail sector. This result is consistent with a study by Kardan, Vadeei, and Imeny [2019], which found that inventory investment optimises inventory performance. By implication, efficient management of the volumes of inventories held by retail firms may improve other inventory-related factors such as decreasing inventory holding, warehouse, insurance, and theft costs. Thus, by optimising inventory-related costs, investment tends to improve the overall inventory performance [Shaaban and Romero-Silva 2021].

Inventory control (β = 0.199; t = 2.457; p = 0.014) also exerted a positive influence on inventory performance. This result confirms the importance of inventory control measures as drivers of a firm's inventory performance, which is in line with previous results [Oballah et al. 2015; Cakir, Bezbradica, and Helfert 2019]. As such, ensuring that optimum levels of inventory are available when required ensures that the inventory management process is effective and efficient.

Further, the results indicate that the use of ABC analysis (β = 0.182; t = 2.060; p = 0.040) contributes to positive inventory performance. This result demonstrates the usefulness of the ABC analysis tool in inventory management processes. ABC analysis is essential in facilitating the effective categorisation of an inventory, making it easier to make decisions on the degree of importance or priority for each item of stock [Nallusamy, Balaji, and Sundar 2017]. Hence, ABC analysis may be considered a strategic inventory management tool and a critical contributor to inventory performance in the retail sector.

It is interesting to note that two inventory management constructs did not contribute to inventory performance. The first is ISP (β = 0.015; t = 0.192; p = 0.848). This result suggests that ISP is not an important contributing factor to inventory performance in the retail sector. A previous study by Shteren and Avrahami [2016] supports the view that the prevention of inventory shrinkage may not necessarily boost inventory performance. In contrast, Munyaka and Yadavalli [2022] found that efforts to prevent the loss of inventory are critical for superior inventory performance and increase the firm's competitiveness. The results of the current study could be indicative of the lack of adequate measures to counter the loss of inventory within the retail sector in South Africa. As reported in a study by Ekegbo et al. [2018], stock shrinkage is prevalent in the South African retail sector and is exacerbated by either the lack of adequate countermeasures or misdirected procedures for minimising it. It is then conceivable that the lack of a link between ISP and inventory performance is linked to the absence of an apparatus that effectively prevents the loss of stock within the retail sector.

The second non-predictive construct was ITO (β = 0.090; t = 1.414; p = 0.158). The result implies that optimising inventory turnover may have no effect on inventory performance in the retail sector. This result contradicts a previous study by Comez-Dolgan and Tanyeri [2015], which promoted ITO as a predictor of inventory performance through its influence on the cost of goods sold to industrial consumers. The unusual result in this study could perhaps be attributed to the period in which data were collected. Data for this study were collected in 2021 at the height of the COVID-19 pandemic. This period was punctuated by several lockdown measures, imposed by the South African government, with negative economic implications for most businesses, including the retail sector. As such, ITO, which accounts for the rate at which inventory was sold and replenished, was skewed during this period for most retail sectors [Redda 2021, **Botha 2022]**. This possibly accounts for the unfamiliar results obtained in the current study.

Inventory Performance and Warehouse Performance

Inventory performance exerted a positive influence on warehouse performance (β = 0.598; t = 12.307; p = 0.000). This result demonstrates that improving the performance of inventory management processes positively impacts warehouse performance. This association emphasises the need for retail firms to optimise their inventory performance as a strategic tool for boosting their warehouse performance. As suggested by some scholars [Islam et al. 2021, Akinlabi 2021], there is a positive link between inventory and warehouse performance. Thus, sustaining warehouse operations calls for developing and investing in the right set of tools for managing inventory [Kusrini, Novendri, and Helia 2018].

CONCLUSIONS AND IMPLICATIONS

The present study tested a research model linking inventory management to warehouse performance in the retail industry in South Africa. The result showed that inventory investment, control, and the utilisation of the ABC analysis tool make a contribution. However, attempts to minimise the loss (shrinkage) of inventory and the number of times inventory is sold and replenished may not be important factors in attempts to enhance inventory performance in that sector. The study also reveals that optimum inventory performance is a determinant factor for successful warehousing.

The study provides new information on the role of inventory management in shaping warehousing performance in the South African retail sector. It identifies those inventory management practices that are essential (inventory investment, control, and the application of ABC analysis) and those that are of minor importance (ISP and ITO) in shaping inventory and warehouse performance.

Practically, the study provides supply chain professionals in the retail sector with information for managing both stock and warehouses. In doing so, attention should be directed to the three practices that exerted a positive impact on inventory performance. Additionally, warehouse performance-related problems can also be traced back to the inventory management practices in place.

To improve inventory performance, the retail sector should invest in advanced technologies such as closed-circuit televisions (CCTV) and radio frequency identification systems (RFID) to strengthen their inventory loss control systems. Automated inventory management systems could be employed to improve its function. However, external consultants who are experts in inventory and warehouse management should be employed to assist retail firms in identifying the most appropriate systems for their businesses. Continuous training of staff working with inventory and within warehouses is essential to update their knowledge and skills.

LIMITATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

The study is limited in that the results are based on the retail sector in two South African provinces, namely Gauteng and KwaZulu Natal. Future studies should also consider other regions that were excluded in the present study. The study considered only five inventory management practices that contributed 23% (r^2=.234) of the variance in inventory performance. Future studies could also include other practices and systems such as inventory accuracy, inventory location, the Six Sigma technique, Just-in-time, vendor-managed inventory, and material requirements planning (MRP) that were excluded in the current study. Additionally, the study was conducted during the COVID-19 era, which could have influenced some of the results (e.g., H3). It may be necessary then to conduct the study using a longitudinal design to obtain an accurate pertain of results. Future studies may also test for moderation using demographic factors such as company size, turnover, and number of years in existence for participating firms.

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ORIGINAL PAPER

USING A GENETIC ALGORITHM TO SOLVE A VEHICLE ROUTING PROBLEM INVOLVING SIMULTANEOUS DELIVERIES AND PICKUPS WITH SPLIT LOADS AND TIME WINDOWS (A CASE STUDY FOR A SHIPPING COMPANY)

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ABSTRACT. Background: This research addresses a Vehicle Routing Problem with Simultaneous Delivery and Pickup, Split Loads, and Time Windows (VRPSDPSLTW). In this research, the VRPSDPSLTW problem is adapted for Company X, a shipping company based in Surabaya. The main goal is to enhance the optimal utilization of vessel capacity in the field of shipping transportation and logistics. Little previous research has been done on VRPSDPSLTW at a shipping company.

Methods: The optimization approach employed was the Genetic Algorithm (GA), which serves as a metaheuristic to effectively optimize vessel capacity utilization. The algorithm uses One Point Crossover and Swap Mutation operators and analyzes various mutation parameters to determine the best configuration. The GA was coded in R, and experiments were conducted to obtain the best parameter for the GA.

Results: The research yielded several outcomes, including route plans, loaded and unloaded Twenty-Foot Equivalent Units (TEUs), travel times, and trip utility from the point of loading (POL) to the point of delivery (POD). In total, there were 85 port visits, surpassing the initial count of 35 ports. Some ports were visited multiple times, with the exception of Surabaya, which served as the home base for a fleet of 15 vessels. The average trip duration was approximately 35 days. Through experimentation, it was determined that employing 1,000 generations along with a mutation probability of 0.2 produces improved solutions. The Genetic Algorithm solution enhanced the average vessel capacity utilization, increasing it to 80.93%. This represents a significant 21.23% increase compared to the global average of 59.7% observed for similar vessel usage scenarios.

Conclusions: Furthermore, through the introduction of novel route opportunities, the contributions of each vessel were effectively enhanced. This achievement resulted in an optimal average vessel capacity utilization that met the demand. The findings strongly advocate for the employment of the Genetic Algorithm, highlighting its potential to substantially improve vessel capacity utilization. Consequently, this approach has played a pivotal role in elevating the efficiency of transportation and logistics operations for Company X.

Keywords: vehicle routing problem, simultaneous deliveries and pickups, split loads, time windows, optimization, genetic algorithm

INTRODUCTION

The Vehicle Routing Problem (VRP) was first analysed by Dantzig and Ramser [1959] to find a solution for fuel delivery. It is now crucial for efficient cargo and travel services, covering various vehicles and customer demands, including sea and air transport. Optimizing delivery routes minimizes costs and travel time and maximizes vessel capacity use in shipping. This involves sequencing visits using multiple vehicles from a central depot [D.M. Utama et al. 2020]. Depot and vehicle capacities, along with customer requests, influence route design [F. Arnold and K. Sörensen 2019]. VRP has evolved into variations like VRPPDTW, which has been explored by researchers like Sitek et al. [2021] and Dewi and Utama [2021].

This research examines Shipping Company X, which has operated in Surabaya (Indonesia)

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since 1984, aiming to enhance its shipping services and economic impact. While offering various services, including port-to-port and international shipping, the company seeks to optimize cargo routes for greater vessel capacity utilization. Current manual processes hinder route efficiency, as evidenced by some vessels operating below 60% capacity. With a fleet of over 40 vessels of varying capacities, simultaneous pickup and delivery, travel time considerations, and load distribution complexities are all significant challenges in route optimization for Company X.

The Genetic Algorithm (GA), by John Holland [1975], optimizes via genetic selection and natural processes, using crossover and mutation. GAs streamline function modeling, reduce errors, and are effective in engineering [J. Protopopova and S. Kulik 2020]. Applied to routing problems [S. Karakatič 2021], GAs address VRP variants, as can be seen in enhanced solutions by M. A. Mohammed et al. [2017], W. Ho et al. [2008], and P. R. de Oliveira da Costa [2018], for delivery efficiency and cost reduction. GA handles capacitated vehicle routing [H. Nazif and L. S. Lee 2012, R. Saxena et al. 2020] and fleet size [S. Liu et al. 2009], and improves VRPTW solutions with decomposition [C.-B. Cheng and K.-P. Wang 2009], which is relevant to VRPSDPSLTW.

This research introduces a customized Genetic Algorithm (GA) to address VRPSDPSLTW challenges for Shipping Company X. It aims to optimize vessel capacity utilization while adhering to split-load, vessel capacity, and travel time constraints. Utilizing historical data (January 2018 to February 2023), with anonymized port and vessel names for confidentiality purposes, it focuses on classifying VRP, particularly VRPSDPSLTW. It incorporates route-specific details such as demand, distances, travel times, and vessel attributes, primarily analyzing Surabaya-based vessels of Company X. The study assumes uniform speed, exclusive vessel use, and a one-week testing period. R is employed for GA, Power BI for visualization, and Minitab for statistical analysis. Notably, the research assumes equal port accessibility and excludes size-based limitations at specific ports.

MATERIALS AND METHODS

The NP-Hard Vehicle Routing Problem (VRP) has drawn significant research interest from researchers seeking to improve efficiency. Traditionally, it assumes a single depot, single-visit customers, and capacity limits. However, real-world scenarios require adjustments. Dror and Trudeau [1989] and Dror et al. [1994] introduced the Split Delivery VRP (SDVRP), dividing customer demands among vehicles to reduce distance and vehicle count.

Overcoming traditional VRP constraints, the Vehicle Routing Problem with Simultaneous Delivery and Pickup, Split Loads, and Time Windows (VRPSDPSLTW) model emerges. It involves vehicles from a depot serving customers while considering simultaneous delivery and pickup within time windows. This applies even when demand surpasses vehicle capacity, enabling multiple visits or multiple-vehicle service. In research by Wang et al. [2013], the VRPSDPLTW method was utilized, with ordered elements denoted as $J = 1,2,3...$, n. $N0$ (where $N0$ includes the depot marked as 0 and 1,2, 3..., n represent customers). Routes involved sequential visits by individual vehicles, connecting successive customers. All routes shared the same depot for departure and return, leading to consistent origins and destinations.

Notations:

Q	capacity of each vehicle
V	set of vehicles, where $k \in V$
V_k	1 if vehicle k is selected to serve a customer, 0 otherwise
J	set of customers $\{1, 2, 3, \dots, n\}$ $\forall i, j \in J$, and $i \neq j$
d_{ij}	travel cost (travel distance) between customer i and customer j
t_{ij}	travel time between customer i and customer j
v_{ij}	travel speed between customer k and customer j
D_j	delivery demand at customer j

R_j	pickup demand at customer j
x_{ijk}	1 if vehicle k travels directly from customer i to customer j, 0 otherwise
y_{ijk}	amount of goods delivered by vehicle k using the route from customer i to customer j
z_{ijk}	amount of goods taken from customer j by vehicle k using the route from customer i to customer j
y'_{ijk}	remaining amount of goods to be delivered form customer i to customer j for vehicle k
$[ai, bi]$	time window for each customer $\forall i \in N0$
r_{ik}	time when vehicle k starts serving customer i.

Objective functions:

$$\min F_1(x) = \sum_{k \in V} |V_k| \sum_{j \in N_0} x_{0_{jk}} \quad (1)$$

$$\min F_2(x) = \sum_{k \in V} \sum_{i \in N_0} \sum_{j \in N_0} d_{ij}\, x_{ijk} \quad (2)$$

Constraints:

$$\sum_{j \in N_0} x_{0_{jk}} = 1 \quad \forall k \in V \quad (3)$$

$$\sum_{i \in N_0} x_{iuk} - \sum_{j \in N_0} x_{ujk} = 0 \quad \forall u \in J, \forall k \in V \quad (4)$$

$$\sum_{i \in N_0} x_{ijk} \geq 1 \quad \forall j \in J, \forall k \in V \quad (5)$$

$$\sum_{k \in V} \sum_{i=0, i \neq j}^{n} y_{ij} = D_j \quad \forall j \in J \quad (6)$$

$$\sum_{k \in V} \sum_{i=0, i \neq j}^{n} Z_{ij} = R_j \quad \forall j \in J \quad (7)$$

$$\sum_{k \in V} \sum_{i \in N} x_{ijk} \geq 1 \quad \forall j \in J, \forall k \in V \quad (8)$$

$$y'_{ijk} + \sum_{i=0, i \neq j}^{n} Z_{ijk} \leq Q \quad \forall j \in J, \forall k \in V \quad (9)$$

$$t_{ij} = \frac{d_{ij}}{v_{ij}} \quad \forall i, j \in J \quad (10)$$

$$r_{ik} + t_{ij} - (b_i + t_{ij} - a_j)(1 - x_{ijk}) \leq r_{jk} \quad \forall j \in J, \forall i \in N_{0,} \ \forall k \in V \quad (11)$$

$$a_i \leq r_{ik} \leq b_i \quad \forall i \in N_{0,} \ \forall k \in V \quad (12)$$

$$r_{ik} + t_{i0} - (b_i + t_{i0} - a_0)(1 - x_{i0k}) \leq b_0 \quad \forall i \in J, \forall k \in V \quad (13)$$

$$r_{0k} = a_0 \quad \forall k \in V \quad (14)$$

$$x_{iik} = 0 \quad \forall i \in N_{0,} \ \forall k \in V \quad (15)$$

$$x_{ijk} \in \{0,1\} \quad \forall i, j \in N_{0,} \ \forall k \in V \quad (16)$$

Objective (1) is intended to minimize vehicles on delivery routes, and objective (2) is intended to minimize travel costs. Constraint (3) ensures each of the k vehicles goes from the depot to customer j in set J. Constraint (4) mandates vehicles to serve customers in sequence before returning to the depot. Constraint (5) permits a single vehicle to serve a customer multiple times. Constraints (6) and (7) define total delivery and pickup demands at customer j. Constraint (8) allows multiple vehicles to serve a customer in varying quantities. Constraint (9) ensures vehicle k's remaining delivery and pickup fit its capacity. Constraint (10) calculates travel time using distance and speed. Constraint (11) regulates the arrival time of vehicle k at customer j after the time $rik + tij$ if vehicle k chooses the route from customer i to customer j or earlier than the difference $aj - bi$ if vehicle k does not choose that route. Constraint (12) enforces service within customer-specified time frames. Constraint (13) requires vehicles to reach the depot before closing time. Constraint (14) sets vehicle departure after the depot opening time a_0.

This research set out to use Genetic Algorithms to effectively optimize simultaneous pickup and delivery in the Vehicle Routing Problem (VRP) and to improve vessel capacity utilization compared to traditional routing methods. The study was intended to develop solutions that consider split-loads, vessel capacity constraints, and travel time constraints, as outlined in the Vehicle Routing Problem Simultaneous Deliveries and Pickups with Split Loads and Time Windows (VRPSDPSLTW). Therefore, the primary objectives of this research were to enhance vessel capacity utilization efficiency within the VRP while maintaining compliance with the constraints specified by VRPSDPSLTW.

The outlined scheme (Fig 1) offers a structured approach to address Company X's issues. It commences with a thorough issue analysis, followed by the establishment of research goals and constraints. A literature review was carried out to gather valuable insights, and initial data was collected. The scheme's core is the development of a Genetic Algorithm-based model for VRPSDPSLTW. Verification and validation tests include a feedback loop for model refinement. The Genetic Algorithm solution was then compared with current conditions, leading to a comprehensive analysis. The scheme culminates in conclusions and recommendations, providing a structured path for addressing Company X's challenges.

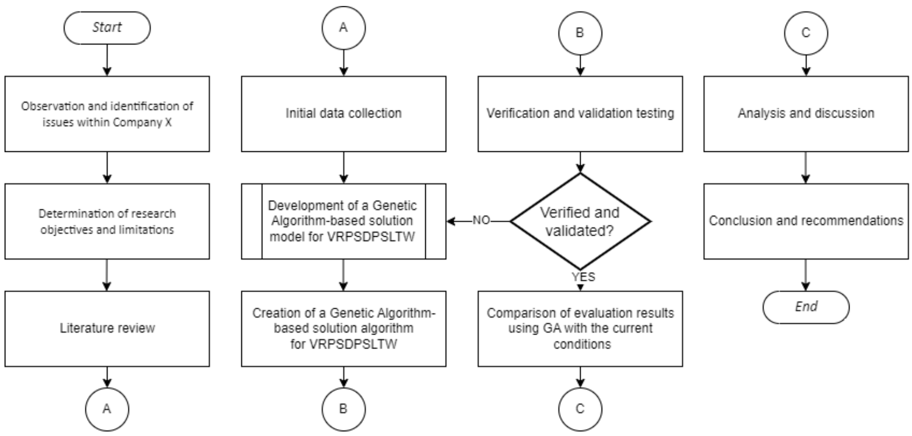

Fig. 1. Flowchart steps of conducted research
Source: Own work

This research employed a variety of data types to implement the Genetic Algorithm effectively using the process shown in the flowchart in Fig. 2. These encompass customer booking details (origin, destination, vessel information, container quantities), port information categorized by region (WEST/EAST), standardized port names, Company X's vessels grouped by homebase, essential vessel specifications (ID, name, dimensions, capacity), detailed cargo delivery records, accurate port-to-port distances and coordinates, and travel durations from port of loading (POL) to port of discharge (POD).

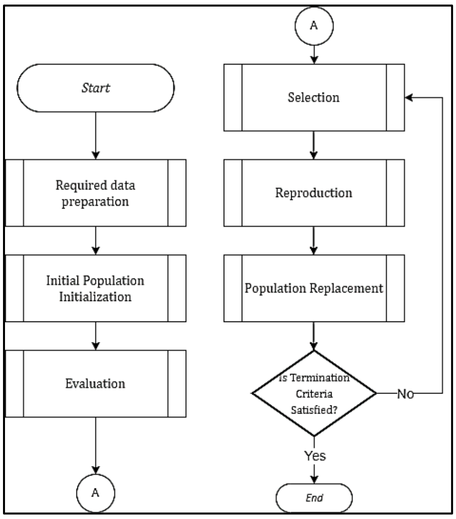

Fig. 2. Flowchart model for solving VRPSDPSLTW based on genetic algorithm
Source: Own work.

The Genetic Algorithm (GA) consists of the following stages: data preparation, Initial Population Initialization, Evaluation, Selection, Reproduction (Crossover and Mutation), and Population Replacement. Iterations continue until the target generation count is reached. Evaluation is crucial, assessing individual quality and performance. It picks individuals with potential traits for better solutions in the next generation. The research employs a fitness value that combines %utility, penalties for demand failure, and overtime. Evaluation follows defined stages and formulas.

Shipping Load (TEUs) = Previous Remaining Journey (TEUs) + Loading Quantity (TEUs) (20)

Remaining (TEUs) = Shipping Load (TEUs) – Unloading Quantity (TEUs) (20)

%Utility = Shipping Load (TEUs) / Payload (TEUs) * 100 (20)

Travel Time (Days) = Shipping Time (Days) + Port Time (Days) (21)

Total Failed Demand (TEUs) = Total Demand (TEUs) – Total Demand Fulfilled (TEUs) (22)

Average %Utility per chromosome = $\frac{\Sigma \text{ (\%Utility from POL to POD in 1 chromosome)}}{\text{Number of POL–POD journeys in 1 chromosome}}$ (23)

Overtime (Days) = (Travel Time of trip 1 (Days) – 31) + (Travel Time of trip 2 (Days) – 31) + ⋯ + (Travel Time of trip n (Days) – 31) (24)

Penalty Time = {0 if Overtime = 0 day (25)
100, if Overtime < 5 days
1000, if Overtime ≥ 5 days}

Penalty Demand = Total Failed Demand (26)

Fitness Value = %Utility – Penalty Demand – Penalty Time (27)

Company X does not enforce a specific time limit for completing a trip, but it does provide standard estimates for sailing hours and port time at each port. For this research, an ideal total travel time per trip was defined as not exceeding 31 days. Any days that surpassed this limit were deemed as overtime, resulting in a penalty. The implementation of penalty time through a Genetic Algorithm (GA) is intended to attain the shortest travel time per trip (penalties are applied to steer the solution towards the 31-day mark), thereby optimizing utility while minimizing unfulfilled demand.

Integrating these elements into the fitness value enables GA to assess route performance. The selection favors higher %Utility and lower Penalty Demand and Time, progressively refining solutions for optimal routes and enhanced vessel capacity utilization. The generated solutions were verified, validated, and adjusted for Company X's needs. Result analysis is intended to produce high-performance solutions aligned with goals. Comparing historical data and constraints is a way of evaluating the effectiveness of improving cargo delivery vessel capacity use.

RESULTS

Data Collection and Analysis

Scenario testing utilized Company X's demand data over a one-week period, which was used as an input for the GA. Table 1 shows the first 5 rows of the booking data that were used as forecast demand and further processed. One TEU is equal to one 20-foot container. In total, 1518 rows of data on forecast demand were collected.

Table 1. Forecast demand for scenario testing

Row	POL	POD	TOTALTEUS
1	IDSUB	IDSSS	57
2	IDGGG	IDSUB	9
3	IDSSS	IDSUB	5
4	IDSSS	IDSUB	1
5	IDSSS	IDSUB	10

Source: Own work.

The TOTAL TEU values for matching POL and POD pairs were subsequently added up. This summed the TEUs for each corresponding POL-POD combination, leading to a data transformation as depicted in Table 2.

Table 2. Aggregated forecast demand based on POL and POD pairs

POL	**POD**	**TEUs**	**POL**	**POD**	**TEUs**	**POL**	**POD**	**TEUs**	**POL**	**POD**	**TEUs**
IDZZZ	IDSUB	7	IDSUB	IDFFF	199	IDNNN	IDSUB	328	IDFFF	IDSUB	352
IDYYY	IDSUB	323	IDSUB	IDGGG	367	IDNNN	IDXXX	1	IDEEE	IDSUB	268
IDXXX	IDSUB	702	IDSUB	IDHHH	70	IDMMM	IDSUB	117	IDDDD	IDSUB	156
IDVVV	IDABC	201	IDSUB	IDJJJ	40	IDLLL	IDSUB	383	IDCCC	IDSUB	33
IDVVV	IDALM	161	IDSUB	IDKKK	375	IDKKK	IDABC	7	IDBBB	IDSUB	892
IDVVV	IDSUB	116	IDSUB	IDLLL	372	IDKKK	IDAEF	18	IDAVW	IDSUB	22
IDVVV	IDXXX	10	IDSUB	IDMMM	207	IDKKK	IDALM	43	IDANO	IDSUB	5
IDSUB	IDAAA	89	IDSUB	IDNNN	123	IDKKK	IDCCC	8	IDAMN	IDSUB	63
IDSUB	IDABC	86	IDSUB	IDPPP	26	IDKKK	IDDDD	53	IDAKL	IDSUB	595
IDSUB	IDAEF	217	IDSUB	IDQQQ	193	IDKKK	IDGGG	35	IDAJK	IDQQQ	3
IDSUB	IDAEG	14	IDSUB	IDSSS	693	IDKKK	IDMMM	48	IDAJK	IDSUB	545
IDSUB	IDAGH	236	IDSUB	IDUUU	54	IDKKK	IDNNN	21	IDAHI	IDSUB	236
IDSUB	IDAHI	238	IDSUB	IDVVV	217	IDKKK	IDQQQ	30	IDAGH	IDSUB	2
IDSUB	IDAJK	117	IDSUB	IDWWW	2	IDKKK	IDSSS	63	IDAEF	IDSUB	125
IDSUB	IDALM	90	IDSUB	IDXXX	158	IDKKK	IDSUB	140	IDAEF	IDYYY	261
IDSUB	IDAMN	94	IDSUB	IDYYY	302	IDKKK	IDUUU	6	IDAEF	IDZZZ	40
IDSUB	IDAUV	9	IDSUB	IDZZZ	35	IDKKK	IDVVV	42	IDABC	IDSUB	18
IDSUB	IDBBB	639	IDSSS	IDSUB	774	IDKKK	IDYYY	26	IDABC	IDXXX	9
IDSUB	IDCCC	203	IDQQQ	IDSUB	217	IDJJJ	IDSUB	94	IDAAA	IDBBB	1
IDSUB	IDDDD	150	IDPPP	IDSUB	36	IDGGG	IDKKK	1	IDAAA	IDSUB	562
IDSUB	IDEEE	114	IDOOO	IDSUB	90	IDGGG	IDSUB	336			

Source: Own work.

To determine port visit counts, the maximum TEUs achieved from past booking and vessel journey data (2018–2022) were identified. The highlighted maximum TEUs (Table 2) were calculated by finding the most transported TEUs from POL to POD in a single vessel journey. Next, unique identifiers were assigned to ports and their visit counts (VISIT) were determined. VISIT represents required visits per port. VISITNR was calculated by dividing TOTALTEUS (demand) by MAXTEUSPERVISIT (highlighted), giving estimated visits. The VISIT column in Table 3 contains rounded VISITNR values. For example, the highest VISIT of 3 for port IDYYY (POD) means 3 visits. Table 4 shows resulting visits for forecast ports. This led to 85 port visits, exceeding the initial 35, as some ports were visited multiple times (except Surabaya, dividing or serving as home base).

Table 3. Example of calculating the number of visits for IDYYY

POL	POD	TOTALTEUS	MAXTEUSPERVISIT	VISITNR	VISIT
IDYYY	IDSUB	323	668	0.484	1
IDAEF	IDYYY	261	523	0.499	1
IDKKK	IDYYY	26	47	0.553	1
IDSUB	IDYYY	302	111	2.721	3

Source: Own work

Table 4. The required number of visits (count) to each port (35 ports in demand data, except for idsub as the home base) for each chromosome

Port	Count	Port	Count	Port	Count	Port	Count	Port	Count	Port	Count
IDAAA	2	IDXXX	2	IDFFF	3	IDKKK	5	IDPPP	1	IDAJK	2
IDBBB	7	IDYYY	3	IDGGG	4	IDLLL	4	IDAEG	1	IDAKL	3
IDCCC	2	IDAUV	1	IDAVW	1	IDMMM	3	IDAGH	3	IDALM	3
IDDDD	3	IDZZZ	1	IDHHH	2	IDNNN	2	IDQQQ	2	IDAMN	2
IDVVV	3	IDANO	1	IDABC	2	IDOOO	1	IDAHI	2	IDUUU	2
IDWWW	1	IDEEE	1	IDJJJ	2	IDAEF	3	IDSSS	5		
Total Count = 85											

Source : Own work

Genetic Algorithm

Here, the decision was taken to establish an initial population with 16 chromosomes, each representing port collections. Genes in a chromosome followed the visit counts in Table 4. Notably, IDSUB is different; it acts as a both start and an end point, dividing chromosomes into trips. The initial Population generated 16 random gene combinations. This ensured diverse starting points. Each chromosome included 35 ports, totaling 85 visits. The initial count of genes in a chromosome was 87 (85 visits + 2 IDSUBs at the beginning and end of the chromosome). However, gene count grows with each generation.

Chromosomes were split into trips via trimming, randomly picking 3 to 7 genes (excluding IDSUB) per trip. The "Subtle" column labels trips, with IDSUBs marking partitions. This breaks 1 chromosome into 15 trips (115 genes), adding 28 new IDSUB genes. Data were reshaped for journey analysis, streamlining the structure for fitness calculation from POL to POD. Table 6 demonstrates this transformation, simplifying the original format.

Table 5. Original data set format

Port	Chromosome	Subgroup
IDSUB	1	A
IDAGH	1	A
IDAUV	1	A
IDBBB	1	A
IDSUB	1	A

Source: Own work

Table 6. Data set format after transformation

POL	POD	Chromosome	Subgroup
IDSUB	IDAGH	1	A
IDAGH	IDAUV	1	A
IDAUV	IDBBB	1	A
IDBBB	IDSUB	1	A

Source: Own work

Table 7. Demand from IDSUB to IDAEF and number of visits to IDAEF

POL	POD	TOTALTEUS	POD VISIT
IDSUB	IDAEF	217	3

Source: Own work

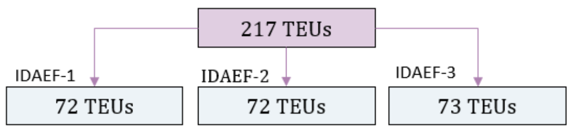

Fig. 3. Concept of split loads for demand from IDSUB to IDAED
Source: Own work

Load-unload quantities were determined based on total TEUs in demand data and visits from relevant ports. For instance, if there was a demand of 217 TEUs from POL IDSUB to POD IDAEF in a given week, with IDAEF visited three times within a chromosome, successful transport required IDSUB (POL) to precede IDAEF (POD). Proportional cargo allocation was crucial, and was achieved by dividing total TEUs by required visits. During three visits from IDSUB to IDAEF, a total of 217 TEUs were transported (Table 7), with allocations of 72 TEUs, 72 TEUs, and 73 TEUs on each visit (Fig. 3). Unsuccessful visits could occur when the POL IDSUB was not visited before the POD IDAEF for all three visits, resulting in untransported demand (145 TEUs if the 2nd and 3rd visits fail, or 73 TEUs if only the 3rd visit fails).

Loading involved direct loading of subsequent ports' demands at each POL. At POD, a specific portion was unloaded. This continued until the trip cargo was 0. The shipping load calculation considered TEUs from POL to POD.

Next, vessel placement maximized each trip's cargo. Each chromosome was assigned a vessel sequentially, matching the cargo to the closest vessel capacity. If this was between ideal and historical capacity, the utility calculations used the maximum cargo. Vessel assignment proceeded until each trip had a vessel. Table 8 demonstrates this process for a trip in one chromosome, outlining load, unload, shipping load, and vessel placement.

Table 8. Example calculation results: load, unload, shipping cargo, and vessel placement in a trip for a single chromosome

POL	POD	Chromosome	Subgroup	LOAD	UNLOAD	Shipping Load	Max Shipping Load	VESSEL ID	VESSEL NAME	PAY LOAD
IDSUB	IDAGH	1	A	188	80	188	188	BBB	BBBBBB	208
IDAGH	IDAUV	1	A	2	9	110	188	BBB	BBBBBB	208
IDAUV	IDBBB	1	A	0	99	101	188	BBB	BBBBBB	208
IDBBB	IDSUB	1	A	136	138	138	188	BBB	BBBBBB	208

Source: Own work

In Table 9, the evaluation results of the fitness values for all chromosomes in the initial population are presented, along with a detailed breakdown of the components contributing to the fitness value.

Table 9. Fitness value calculation results for all chromosomes in the initial population

Chromosome	%Utility	FAILED	PENALTYDEMAND	OVERTIME	PENALTYTIME	fitness value
1	80.23	880	880	166	1000	-1799.77
2	77.2	943	943	130	1000	-1865.8
3	77.22	589	589	147	1000	-1511.78
4	73.91	960	960	145	1000	-1886.09
5	76.67	862	862	131	1000	-1785.33
6	75.76	1024	1024	127	1000	-1948.24
7	75.64	811	811	116	1000	-1735.36
8	79.88	909	909	90	1000	-1829.12
9	78.6	927	927	108	1000	-1848.4
10	76.07	928	928	143	1000	-1851.93
11	80.01	867	867	141	1000	-1786.99
12	76.52	799	799	105	1000	-1722.48
13	73.09	759	759	115	1000	-1685.91
14	77.09	898	898	129	1000	-1820.91
15	75.74	729	729	111	1000	-1653.26
16	74.62	777	777	109	1000	-1702.38

Source : Own work

Subsequently, selection probability was calculated by dividing each individual's fitness value by the total fitness value of the population, establishing probabilities for the mating pool. Employing the roulette wheel method, individuals were chosen for the pool using a random number in the "rand" column. The first chromosome with a cumulative probability exceeding the random number entered the pool. After pool selection, individuals were paired as parent pairs for crossover or genetic recombination if criteria were fulfilled, as shown in Table 10.

Table 10. Roulette wheel results and parent pairs for crossover

rand	Chromosome	Cumulative probability	Pair	rand	Chromosome	Cumulative probability	Pair
0.722	12	0.738	1	0.966	16	1	5
0.08	2	0.1277	1	0.378	7	0.4059	5
0.041	1	0.0657	2	0.316	6	0.3477	6
0.814	14	0.8675	2	0.489	9	0.5381	6
0.597	10	0.6041	3	0.468	8	0.4716	7
0.497	9	0.5381	3	0.239	4	0.2439	7
0.663	11	0.6693	4	0.969	16	1	8
0.131	3	0.1915	4	0.408	8	0.4716	8

Source : Own work

After obtaining chromosome pairs, the subsequent step involved selecting pairs for crossover using a crossover probability (Pc) set at 0.9. Crossover occurs if the randomly generated number for each pair is below 0.9. Employing one-point crossover, a random cutting point is assigned to each pair. Chromosomes serve as "parents," yielding two offspring or "children" with equal chromosomes. Initial mutation probability (pm) ranges from 0.01 to 0.2 for real-world optimization. Following crossover, each chromosome's randomly generated number between 0 and 1 determines mutation. If the number is below pm, the chromosome mutates, exchanging two random gene points (swapping mutation) and forming a new offspring chromosome.

New offspring resulting from crossover and mutation are merged with the initial population, then evaluated for fitness. Retaining the two best chromosomes, merged chromosome averages are calculated. If the target generation is not reached, chromosomes ranked from 3rd to 100th become the next generation's initial population, ensuring genetic diversity and optimal outcomes.

Optimization Results of Scenario Testing

In this research, the optimization of GA solutions for the VRPSDPSLTW problem consisted of three key variables: population size, mutation probability, and crossover probability. The crossover probability was set at 0.9, and the initial population size was 16 individuals. The mutation probability was tested at 0.01 and 0.2, each repeated five times with the same initial population size and 500 generations per trial. Analysis of the best fitness value graphs in Fig. 4 and Fig. 5 reveals convergence at the 500th generation for both mutation probabilities. Consequently, it can be inferred that under these conditions, mutation probabilities of 0.01 and 0.2 yield similar qualities, facilitating a meaningful comparison.

Table 11. Analysis of mutation probability parameters

Replicaton	First Best Fitness Value		%Utility		Failed Demand (TEUs)		OverTime (Days)	
	pm = 0.01	pm = 0.2	pm = 0.01	pm = 0.2	pm = 0.01	pm = 0.2	pm = 0.01	pm = 0.2
1	-978.6	-920.85	76.4	81.15	55	2	141	101
2	-980.8	-929.72	72.2	79.28	53	9	103	125
3	-931.05	-921.18	79.95	79.82	11	1	115	127
4	-938.98	**-919.11**	79.02	80.89	18	**0**	153	116
5	-939.78	-928.74	80.22	80.26	20	9	124	79
Mean	-953.84	-923.92	77.56	80.28	31.4	4.2	127.2	109.6
Worst	-980.8	-929.72	72.2	79.28	55	9	153	127
Best	-931.05	**-919.11**	80.22	81.15	11	0	103	79

Source: Own work

Based on the findings in Table 11, a mutation probability of 0.2 demonstrates the highest potential for achieving optimal fitness values. In this research, higher fitness values indicated improved performance and closer alignment with objectives. Remarkably, the peak fitness value of -919.11 was achieved with a 0.2 mutation probability, surpassing the 0.01 probability results. The subsequent sections delve deeper into these optimal fitness value variables and compare them with the current conditions. The consistency of testing with a mutation probability of 0.2 is evident, as the best solution (-919.11) closely matches the average of all tests (-923.92). Fig. 4 and Fig. 5 provide supporting visuals, showcasing the best fitness values for mutation probabilities of 0.01 and 0.2, respectively.

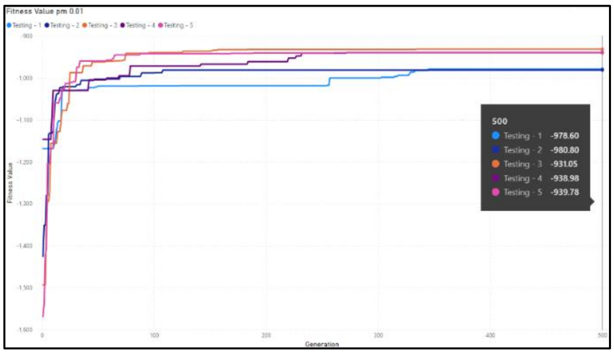

Fig. 4. The best fitness values for each generation with 500 generations and a mutation probability of 0.01 for each test
Source: Own work

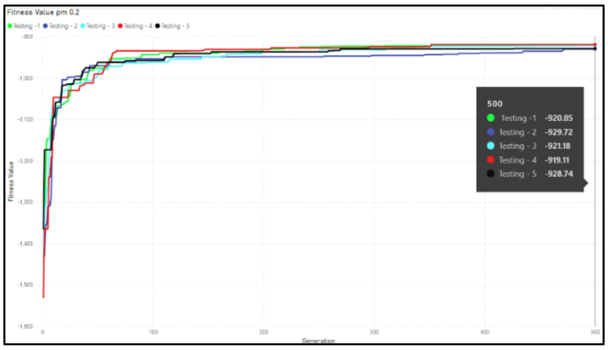

Fig. 5. The best fitness values for each generation with 500 generations and a mutation probability of 0.2 for each test
Source: Own work

The optimal fitness value achieved after 500 generations of testing was -919.11, representing a substantial improvement of 21.13%. This signifies that the average % capacity utilization of the tested vessels reached 80.89%, exceeding the historical average % capacity utilization of all vessels in Company X's history, which was 59.76% based on the data from previous operations. A mutation probability of 0.2 exhibits a higher likelihood of producing better results compared to 0.01. Although convergence solutions were achieved using 500 generations, the solution still shows a sloping, increasing trend; therefore the number of generations was increased to 1000. The number of generations was also increased to further reduce the number of overtime days. Fig. 6 presents the best fitness values for each generation with 1000 generations for each test, while Table 12 provides detailed results for each test with 1000 generations.

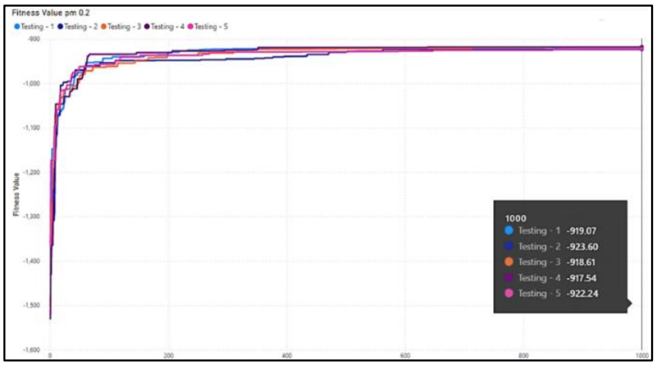

Fig. 6. Best fitness values across 1000 generations with a mutation probability of 0.2 for each test
Source: Own work

Table 12. The results of five replications with a mutation probability of 0.2 and 1000 generations

<table>
<tr><th rowspan="2">Replication</th><th colspan="2">First Best Fitness Value</th><th>%Utility</th><th>Failed Demand</th><th>OverTime</th></tr>
<tr><td colspan="2">pm = 0.2</td><td>pm = 0.2</td><td>pm = 0.2</td><td>pm = 0.2</td></tr>
<tr><td>1</td><td colspan="2">-919.07</td><td>80.93</td><td>0</td><td>94</td></tr>
<tr><td>2</td><td colspan="2">-923.6</td><td>78.4</td><td>2</td><td>138</td></tr>
<tr><td>3</td><td colspan="2">-918.61</td><td>82.39</td><td>1</td><td>123</td></tr>
<tr><td>4</td><td colspan="2">-917.54</td><td>83.46</td><td>1</td><td>115</td></tr>
<tr><td>5</td><td colspan="2">-922.23</td><td>79.76</td><td>2</td><td>76</td></tr>
<tr><td>Mean
(1000
generations)</td><td colspan="2">-920.21</td><td>80.99</td><td>1.2</td><td>109.2</td></tr>
<tr><td colspan="6">Current Best Solution:</td></tr>
<tr><td colspan="2">First Best Fitness Value</td><td colspan="2">%Utility</td><td>Failed Demand</td><td>OverTime</td></tr>
<tr><td colspan="2">-919.11</td><td colspan="2">80.89</td><td>0</td><td>116</td></tr>
<tr><td colspan="6">Mean of mutation probability 0.2 with 500 Generations (all tests)</td></tr>
<tr><td colspan="2">First Best Fitness Value</td><td colspan="2">%Utility</td><td>Failed Demand</td><td>OverTime</td></tr>
<tr><td colspan="2">-923.92</td><td colspan="2">80.28</td><td>4.2</td><td>109.6</td></tr>
</table>

Source: Own work

Test 4, with 1000 generations, outperformed the previous best solution with higher %Utility (+2.57%), lower Overtime (-1 day), and improved fitness value (+1.57). However, it experienced unmet demand, impacting %Utility. As a result, Test 1 was chosen as the best solution, showing increased %Utility (+0.04) and reduced Overtime (-22 days) compared to the previous best solution, with no failed demands, providing more consistent results than Test 4. Although Test 500 met individual requirements, Test 1000 showed potential for better overall solutions with higher %Utility, lower demand failure rate, and shorter delivery times.

The increase in fitness value per generation from the optimal solution is visualized in Fig. 7. The visualization includes the second-best fitness value and the average fitness value of the entire population for each generation.

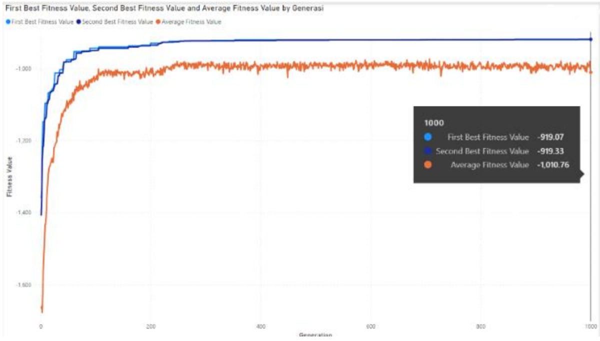

Fig. 7. Trend of fitness value per generation for the optimal solution
Source: Own work

Table 13 provides a detailed breakdown of the output from the GA process that led to the optimal fitness value from a total of 15 trips (the table displays one sample trip). Fig 8. represents the practical results obtained from this single sample trip from a total of 15 trips. It presents the planned routes to fulfill the designated demand, including the load and unload quantities, utility, and time required for each journey between POL and POD.

Furthermore, the output also provides information regarding the average % capacity utilization of the vessel for the entire voyage (80.93%), no failed demand (0 TEUs), and the total sum of overtime for the entire journey (94 days). The following section will present a comprehensive analysis of these variables.

Table 13. Output of GA process for optimal fitness value (1 out of 15 trips)

POL	POD	Chromosome	Subgroup	LOAD	UNLOAD	Shipping Load	VESSEL ID	VESSEL NAME	PAY LOAD	% UTILITY TRIP	TOTAL TIME DAYS
IDSUB	IDAMN	66	A	193	46	193	TTT	TTTTTTT	453	42.6	6.14
IDAMN	IDFFF	66	A	31	67	178	TTT	TTTTTTT	453	39.29	5.7
IDFFF	IDAKL	66	A	118	0	229	TTT	TTTTTTT	453	50.55	5.51
IDAKL	IDAGH	66	A	199	80	428	TTT	TTTTTTT	453	94.48	4.48
ADAGH	IDSUB	66	A	2	350	350	TTT	TTTTTTT	453	77.26	2.07

Source: Own work

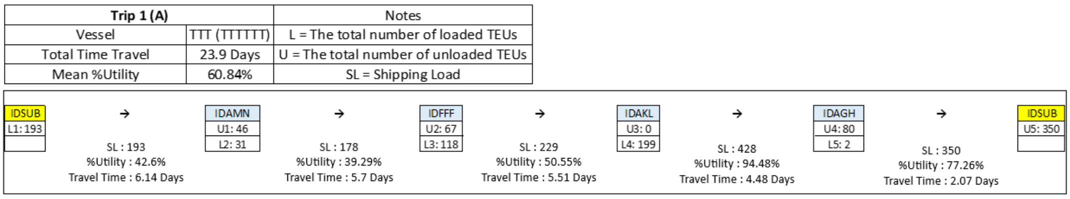

Fig. 8. Practical illustration of GA solution (1 out of 15 trips)
Source: Own work

The case study results displayed successful TEU demand, but various scenario tests uncovered potential forecast demand failures. In such cases, unmet demand and its POL and POD origins can be identified. Solutions include adapting forecast targets or allocating unmet demand to future trips.

Table 14 shows the required time for each trip to return to the home base in the proposed solution. This total time includes travel time from all POL to POD on the trip, added to port time (idle time of the vessel), and measured in days. Currently, the company does not have an ideal figure to determine how long one trip should take to fulfill the demand. Therefore, in the implemented GA program, the authors apply high penalties to solutions with significant total overtime (days > 31) across all trips. This is to minimize the total time of each journey, getting it as close as possible to the ideal figure. The results show that to meet the demand in the real-case scenario test, 15 trips were required with an average delivery time of 35.57 days.

The case study results revealed no failed TEU demand in the utilized scenario, yet various tests demonstrated potential forecast demand inaccuracies. In such instances, unfulfilled demand and its POL and POD origins can be displayed. Addressing this entails options like refining forecast targets or allocating unfulfilled demand to future trips, requiring careful consideration of utility maximization, demand fulfillment, and travel time trade-offs during the GA optimization process. Optimization focus adjustments can be realized by reevaluating parameters and penalty functions.

Table 14. The time taken by each trip from homebase to return to homebase

	Trip	VESSELID	VESSELNAME	**TOTALTIME (Days)**	**%UTILITY TRIP**
1	A	TTT	TTTTTT	23.90	60.8389
2	B	GGG	GGGGGG	25.01	71.8056
3	C	ABO	ABOABO	30.38	81.7243
4	D	WWW	WWWWWW	40.53	93.6330
5	E	ABY	ABYABY	54.22	68.3165
6	F	PPP	PPPPPP	46.16	79.2683
7	G	ABU	ABUABU	36.18	74.1385
8	H	OOO	OOOOOO	36.72	87.8021
9	I	BBB	BBBBBB	31.02	91.4530
10	J	ABS	ABSABS	48.54	79.9195
11	K	ABR	ABRABR	32.32	80.1060
12	L	QQQ	QQQQQQ	37.86	91.1635
13	M	RRR	RRRRRR	36.61	77.6126
14	N	ABI	ABIABI	24.51	86.2894
15	O	YYY	YYYYYY	29.51	89.8960
Mean				35.57	80.93

Source: Own work.

The GA program penalized solutions exceeding 31 days of overtime across trips to align with benchmarks, due to the absence of a standard trip duration. Real-case testing demanded 15 trips for demand fulfillment and successfully achieved an average trip time close to 31 days, specifically averaging 35.57 days, representing optimal results.

In the same table, the average vessel capacity utilization percentage for all trips is presented. This data offers a clear overview of trip-level utilization. Notably, each trip's average utilization surpasses 60%, with an overall average of 80.93%. These findings indicate a fairly optimal ship capacity utilization level from the GA algorithm. In the detailed analysis, the GA solution's utilization is compared with historical data to assess improvements in ship capacity utilization.

Table 15 shows the utility evaluation results for the selected vessel in GA scenario testing. "Result Utility" indicates post-GA optimization, while "History Utility" portrays historical usage (2019–2022) without GA, reflecting actual fulfillment rates. Notably, a 21.23% increase is observed. Fig. 9 further illustrates the positive impact of GA, with improved vessel performance in capacity utilization. All vessels experienced enhanced utility after GA optimization, showcasing its positive contribution to effective vessel capacity utilization for cargo delivery.

A t-test was conducted, with the null hypothesis (H0) that there was no difference between the population means of Result %Utility and History %Utility, and the alternative hypothesis (H1) that there was a higher mean for Result %Utility. The t-test results (P-Value (0.000) < alpha (0.05)) led to the rejection of H0 and the acceptance of H1. This indicates a substantial increase in the mean of Result %Utility in comparison to History %Utility.

Table 15. Results of utilization evaluation for the involved vessels in solving scenario tests with GA.

VESSELID	VESSELNAME	% Result Utility	% History Utility
ABS	ABSABS	79.92%	68.12%
TTT	TTTTTT	60.84%	55.54%
ABR	ABRABR	80.11%	54.64%
ABY	ABYABY	68.32%	57.36%
YYY	YYYYYY	89.90%	61.49%
BBB	BBBBBB	91.45%	66.23%
GGG	GGGGGG	71.81%	54.65%
RRR	RRRRRR	77.61%	52.20%
ABI	ABIABI	86.29%	76.32%
ABO	ABOABO	81.72%	53.46%
PPP	PPPPPP	79.27%	59.19%
OOO	OOOOOO	87.20%	63.22%
QQQ	QQQQQQ	91.16%	60.36%
WWW	WWWWWW	93.63%	46.76%
ABU	ABUABU	74.14%	65.67%
Mean		80.93%	59.70%

Source: Own work

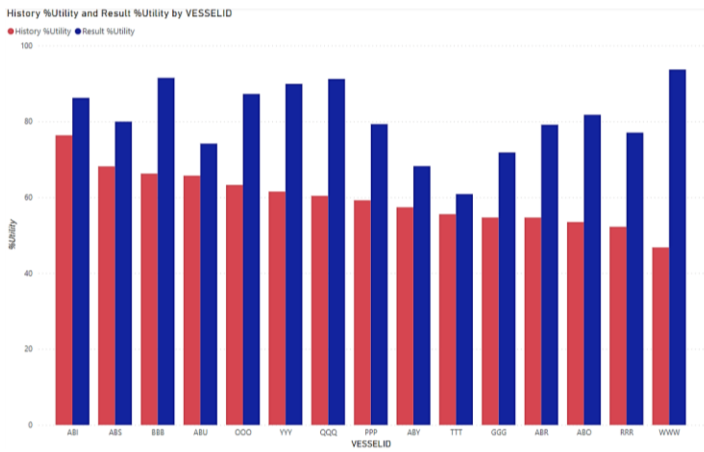

Fig. 9. Clustered Column Chart: Historical % Utility vs. % Utility Results Using GA

DISCUSSION

Comparing our study with research by Wang et al. [2013], both achieved substantial resource utilization enhancements, albeit in different contexts. Wang et al. [2013] improved land-based vehicle loading efficiency by 12.8% using a Hybrid Heuristic Algorithm inspired by local search. In contrast, our study focused on maritime operations, raising vessel capacity utilization by a remarkable 21.23%, from 59.7% to 80.93%, using a Genetic Algorithm.

This comparison highlights the versatility of VRPSDPSLTW optimization across logistics domains. Whether on land or at sea, optimization methodologies promise improved resource utilization. While Wang et al. [2013] employed a Hybrid Heuristic Algorithm, we used a Genetic Algorithm, addressing the same core problem of simultaneous deliveries and pickups with split loads and time windows (VRPSDPSLTW). These findings contribute to the discourse on optimizing logistics across diverse contexts.

CONCLUSION

The Genetic Algorithm (GA) effectively tackled the complex VRP with simultaneous pickup and delivery, split-loads, vessel capacity, and time window constraints (VRPSDPSLTW) optimization problem. Employing GA with 1000 generations, 0.9 crossover probability, and 0.2 mutation probability, vessel capacity utilization significantly rose to 80.93%, a remarkable 21.23% enhancement from the prior 59.7%. GA innovatively devised routes, yielding superior capacity utilization while considering empty container loads. Notably, the GA solution adeptly managed port visits, split-loads, time, and vessel capacity for POL to POD trips. The average trip duration was approximately 35 days, aligning closely with the 31-day target. Achieving a 100% sales target validated GA's efficacy.

However, it is essential to acknowledge the study's limitations. The research relied on anonymized historical data within a specific timeframe and uniform assumptions. Software choices simplify the model but might not account for the nuances of real-world operations. Additionally, the assumption of equal port accessibility and the exclusion of size-based limitations at specific ports could affect the generalizability of the findings. These limitations should be considered when interpreting the results and offer opportunities for further research to refine the model and address these constraints. Future research endeavors could explore multi-objective GA approaches for conflicting goals and incorporate real-world factors such as stochastic voyage time and time-dependent demand to enhance the applicability of the optimization solution.

RECOMMENDATIONS

To enhance the GA's performance in future research, the following suggestions can be considered:

- Modify the crossover operator: Test different crossover operators to explore the possibility of finding more efficient solutions for the VRPSDPSLTW context.
- Consider weather factors: Analyze the impact of weather conditions on vessel voyages for the researched routes and evaluate their effects on travel time.
- Expand research to involve all Company X's vessels from various homebases, including Jakarta port as the homebase for vessel journeys, and consider demand for all POL to POD services from the west and east regions.

By taking these recommendations into account, future research is expected to provide solutions that are closer to actual conditions, more efficient, and optimal in resolving the VRPSDPSLTW problem.

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ORIGINAL PAPER

IMPACT OF SUPPLY CHAIN MANAGEMENT PRACTICES ON INNOVATIVE PERFORMANCE: MEDIATING ROLE OF ORGANIZATION COMPETENCE AND COLLABORATIVE CAPABILITIES AS MODERATOR IN SME SECTOR

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ABSTRACT. Background – Supply chain management practices can contribute towards firm performance whether financial or non-financial. This study thus aims to examine the impact of supply chain management (SCM) practices on innovative performance of small and medium-sized enterprises (SMEs) in Pakistan. The study also investigates the role of organizational competence as a mediator between SCM and innovative performance. Furthermore, organizations' collaborative capabilities have been proposed as a moderator between SCM and organizational competence.

Methods– A questionnaire-based survey with 201 top executives of SMEs in the manufacturing, services, and trading sector of Punjab province of Pakistan was conducted in this study.

Results – The results show a significant positive relationship between supply chain management practices and the innovative performance of an organization. The role of organization competence as a mediator was also found to be significant. Furthermore, it has also been established that the collaborative capabilities of an organization play its positive role to enhance relationship between SCM practices and organizational competence.

Conclusions – The current study provides evidence of a relationship between SCM practices and innovative performance of SMEs. The results suggest that efforts should be directed at improving supply chain management practices in SMEs to enhance innovative performance through organizational competence. In addition, collaborative capabilities enhance the organizational competence of SMEs with the implementation of SCM practices.

Keywords: Supply chain management practices, Innovative performance, Small and medium-sized enterprises (SMEs), Collaborative capabilities, Organization competence.

INTRODUCTION

The role of small and medium enterprises (SMEs) is imperative for developed and developing countries around the world [Benjamin et al., 2021]. SMEs significantly contribute to the overall growth of the economy and are a major source of job creation. Globally, SMEs contribute to over 90 percent of businesses, and more than half of the world's workers belong to the SME sector. Consistent with the global data, Pakistan's SME sector also constitutes more than 90 percent of businesses, and its contribution to gross domestic product (GDP) and total export of the country is 40 percent [Competition Commission of Pakistan 2021]. The definition of SMEs varies in different economies, and in Pakistan based on a prudential regulation issued by the State Bank of Pakistan, businesses with up to 250 employees and an annual sales turnover of Rs.800.00 million fall under the SME category [State Bank of Pakistan 2022].

It is evident from the existing literature that SMEs are more prone to supply chain deficiencies, which hamper their growth and are a major hindrance in way of their competitiveness. Supply chain disruptions cause more damage to SMEs than to large firms [Thun et al., 2011, Ali and Geologeci, 2019], owing to

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the scarcity of resources in SMEs [Arsawan et al., 2020, Thun et al., 2011] and inadequate preparation to absorb supply chain [Wedawatta et al., 2010]. The failure rate for SMEs is on the rise across the world [Arsawan et al., 2020]. However, these challenges can be managed effectively by implementing supply chain practices in SMEs. Supply chain management practices like handling customer relationships, real-time sharing of information, and strategies to effectively engage business partners are imperative for giving competitive advantages to SMEs [Afraz et al., 2021, Huo et al., 2021, Migdadi, 2021, Li et al., 2006].

Supply chain management (SCM) practices encompass the integration of all stakeholders, which includes suppliers, manufacturers, distributors and customers, in such a way that the overall improved long-term performance of the individual firm is achieved through efficient supply chain management practices [Chopra and Meindl, 2001]. SCM practices play a significant role in bringing innovation to business through innovative products and procedures [Srivastava et al., 1999]. Innovation is an ongoing process to regularly introduce new products/services and procedures in the market or bring changes in the existing products to cater for the growing needs of the business [OECD, 2005]. SCM practices help in developing joint strategies which help in improving the production process and ultimately lead to the development of better and newer products [Kaminski et al., 2008].

Previously, researchers investigated dynamic SCM practices in relation to SMEs and pointed towards the effectiveness of these practices for SMEs [Quayle, 2003, Arened and Wisner, 2005, Bhutta et al., 2007, Towers and Burnes, 2008, Bordonaba-Juste and Cambra-Fieero, 2009, Welker et al., 2008]. Research suggests that SMEs have benefited in terms of competitive advantages by applying SCM practices [Bordonaba-Juste and Cambra-Fieero, 2009] and these practices help improve the performance of SMEs [Bhutta et al., 2007]. More recently, it has also been reported that SCM practices can help in the operation and financial performance of SMEs [Lee, 2021]. Thus, it is imperative to look into the relationship between SCM practices and innovative performance. In this regard, this study aims to address the following research questions. Do SCM practices influence the innovative performance of SMEs in a developing economy i.e. Pakistan? Additionally, to what extent does organizational competence provide a path through which these SCM practices improve the innovative performance of SMEs? Likewise, the study also tests how collaborative capabilities of firms can help in enhancing the SCM practices-organizational competence relationship.

This model is in line with the resource-based view i.e. RBV of the firm. According to RBV [Barney, 1991], firm resources and capabilities are a source of sustainable competitive advantage for the firms. SCM practices can be resources which help enhance organizational competence and innovative performance, therefore becoming a source of sustainable competitive advantage for SMEs. Thus, studying these relationships may help SME managers to better identify the ways to enhance innovative performance and decide on the implementation of SCM practices. This study advocates promoting innovation in SMEs through SCM practices. It further addresses the relationship between SCM practices and the innovative performance of SMEs through organizational competence. In addition, this study explores the moderating role of collaborative capabilities in relations between SCM practices and organizational competence. Overall, enhancing innovative performance in SMEs also contributes to the achievement of United Nations (UN) sustainable development goal number 9 i.e. industry, innovation, and infrastructure, which provides additional motivation for the research.

Supply Chain Management Practices: An Overview

Supply chain management (SCM) practices aim to promote competent management of organization supply chain by using a set of activities. Li et al. [2005] developed six comprehensive, empirically tested dimensions of SCM practices, which include partnership with supplier, relationship with clients, sharing information, quality of information, lean practices adopted internally, and postponement.

Firstly, there is maintaining a long-term relationship between the organization and partnership with supplier. Secondly, the customer relationship focuses on three core areas pertaining to customers including complaint handling, taking feedback from customers to measure their level of satisfaction, and promoting a long-term relationship between an organization and its customers. Thirdly, sharing information is a key dimension which ensures the flow of information to all stakeholders in order to make effective and timely decisions. Fourthly, the quality of information in terms of accuracy and adequacy in timely manners. Fifthly, lean practices mainly deal with maintaining the optimal level of inventory through effective waste management. Sixthly, as dealing with delays in the supply chain is the top priority, postponement strategies fit in this dimension.

The impact of SCM practices has been studied by various scholars in past. For example, according to Ragatz et al. [1997], SCM practices such as strategic suppliers significantly impact on the competitive advantages of an organization. Sharing good-quality information leads to customer satisfaction and the quality of information also helps to increase customer satisfaction [Spekman et al., 1998]. According to Van Hoek et al. [1999], global efficiency and customer responsiveness is achieved through handling postponements in the supply chain process. Recently conducted studies further confirm that SMC practices such as relationships between buyers and seller [Afraz et al., 2021], sharing quality information [Huo et al., 2021] and managing customer relations [Middadi 2021] lead firms towards competitive advantage.

Supply Chain Management Practices and Innovative Performance

Innovative performance is defined as companies' achievements in various fields related to developing new ideas, launching new devices / products, and introducing new improved processes and systems [Ernst 2001, Freeman and Soete 1997]. In the broader perspective, innovative performance is divided into two distinctive categories: production innovation and innovation in process [Prajogo and Sohal, 2003, Gunday et al., 2011, Kim et al., 2012]. Five major dimensions of organizational innovativeness were defined by Vigoda-Gadot et al. [2005], which include: creativity, risk taking, acceptance and adoption of changes, future orientation, and pro-activeness. Subramanian and Nilakanta [1996] divided innovation practices in two main components: technical innovation, which pertains to innovation in services, processes, and products, and the second type, innovation dealing with structure, administration and process and program-related administrative work.

SCM practices promote the development of competitive advantages in SMEs, and these practices effectively engage clients and suppliers [Bordonaba-Juste and Cambra-Fierro, 2009]. Both general and operational performance are included in this development [Bayraktar et al., 2009], which provide support for innovative processes in the firm [Zeng et al., 2010]. A strong connection between suppliers and client collaborative practices and innovation in products among Korean SMEs were also reported in previous research [Chun and Mun 2012]. Canadian SMEs also support engaging suppliers through the use of technology to promote innovation [Drayse, 2011]. Similarly, other studies across the world revealed a connection between different dimensions of SCM practices and innovation processes in SMEs [Doloreux, 2004, Wang and Kafouros, 2009].

According to the resource-based view [Barney, 1991], organizational resources such as SCM practices are a source of competitive advantage. A competitive edge can be developed by implying SCM practices mainly engaging suppliers and customer [Bordonaba-Juste and Cambra-Fierro, 2009]. Likewise, vertical integration of suppliers and customers leads to cost competitiveness [Arend and Wisner, 2005]. Other studies also showed that operational and general performance is improved by the implementation of SCM practices in firms [Bayraktar et al., 2009, Bhutta et al., 2007].

As regards innovation, it is well established from previous studies that effective engagement between suppliers and customers leads to innovation in SMEs. A study conducted in Brazil by Kaminski et al. [2008] established that innovation is a motivational force in creating effective suppliers and customer coordination. Similarly, in the Korean context, Drayse (2011) validated the same concept, showing that collaborative practices between suppliers and customers facilitate innovation process in organizations. According to Doloreux (2004), innovation in processes brings about strong bonds among suppliers and customers. From the business point of view, a study by Ho et al. [2004] also highlighted that close collaboration between suppliers and customers is a result of innovation in processes and products of organization. Abereijo et al. [2009] further validated that the relationship between supplier and customer provides a strong base for innovation in organizational processes. Based on the abovementioned arguments, we propose that.

Hypothesis 1: Supply chain management practices have a significant positive effect on innovative performance of an organization.

Mediating Role of Organizational Competence between SCM Practices and innovative Performance

Organizational competence is a broad term which includes several components like capabilities, abilities, skills, and resources [Athey and Orth 1999, Prahalad and Hamel 1990, Sanchez 2004]. From the supply chain management perspective, organizational competencies are classified into four major categories i.e. functional competence, relational competence, managerial competence and behavioral competence [Derwik and Hellstrom, 2017]. According to these researchers, functional competence lies in the process and functions of the organization; we can measure functional competence from the operational and strategic levels, relational competence deals with the integration of different stakeholders like customers, suppliers, partners, management and employees. Managerial competency entails specific tasks, which are related to management aspects like resources management and strategy development. The final classification of competence is behavioral competency, which deals with a unique aspect of competency related to attitudes and characteristics.

Organizational competence has been measured in the past by relying on both non-financial and financial aspects [Koh et al., 2007]. Organizational competence and overall achievement of organizational objective go side by side [Hamon, 2003]. In the current study, we limit organizational competence to four dimensions, as defined by Tippins and Sohi [2003], which are relative profitability, growth in sales, retention of customers and growth in overall sales of organization. SCM practices significantly impact organizational competence, which further leads to innovative performance. When organizations implement various SCM practices, including customer relationship building, strategic supplier partnership, and dealing with delays, all these practices help the organization to get a competitive advantage in terms of cost, flexibility, quality, and dependability, which further improves organizational performance [Li et al., 2021]. SCM integration among suppliers, organizations and customers facilitates the transfer of knowledge, thus helping the organization to adapt and change according to advancements and developments in the market [Alkalha et al., 2019]. Moreover, SCM efficiency enhances the organizational competence and ultimately improves the performance of the organization [Wang et al., 2016]. Based on the above discussion, we hypothesize the following.

Hypothesis 2: Organizational competence mediates the relationship between SCM practices and innovative performance.

Collaborative Capabilities as Moderator between SCM Practices and Organizational Competence

Collaborative capabilities are essential for efficient and effective supply chain management processes. The exchange of information is a fundamental aspect of collaborative capabilities of any organization [Barratt, 2004]. Likewise, another important benefit derived from collaborative capabilities ensures the real-time flow of information [Whipple and Russell, 2007]. In past research, the collaborative capabilities of organization have been studied with respect to information sharing, joint decisions and operational efficiency. For example, for Daugherty et al. [2006], collaboration is about the real-time flow of information, making strategic plans jointly and managing the firm's operations with respect to changing requirements regarding shared information. Cao et al. [2010] conducted a detailed conceptualization of the collaborative capabilities of organizations and defined constructs which strengthen relationships in diverse supply chain management practices by sharing information, setting performance goals, making decision jointly, sharing business resources, aligning incentives with performance, and by effective communication and knowledge creation.

In any firm, collaborative activities play a vital role in enhancing organizational performance [Wang and Hu, 2020]. Previous research has shown that collaborative innovation capabilities help the firm to replicate knowledge among the firms and their supply chain networks through interactive activities [Mishra and Shah, 2009]. Extensive research has explored how firms acquire resources and develop their capabilities for supply chain management [Biotto et al. 2012]. Based on the resource-based view, firm's resources and capabilities help to get competitive advantage [Huo 2012]. When firms implement unique resources in the form of SCM practices and collaborative capabilities then they can achieve a competitive advantage in the form of organizational competence. Organizational competence based on relational competency integrates different stakeholders in supply chain management process [Derwik and Hellstrom 2017]. Thus, in the presence of collaborative capabilities and SCM practices, diverse dimensions of organizational competence are expected to be strengthened. Therefore, on the basis of the above discussion, we propose the following hypothesis.

Hypothesis 3: Collaborative capabilities moderate the positive relationship between supply chain management practices and organization competence in such a way that the relationship will be stronger when collaborative capabilities are high.

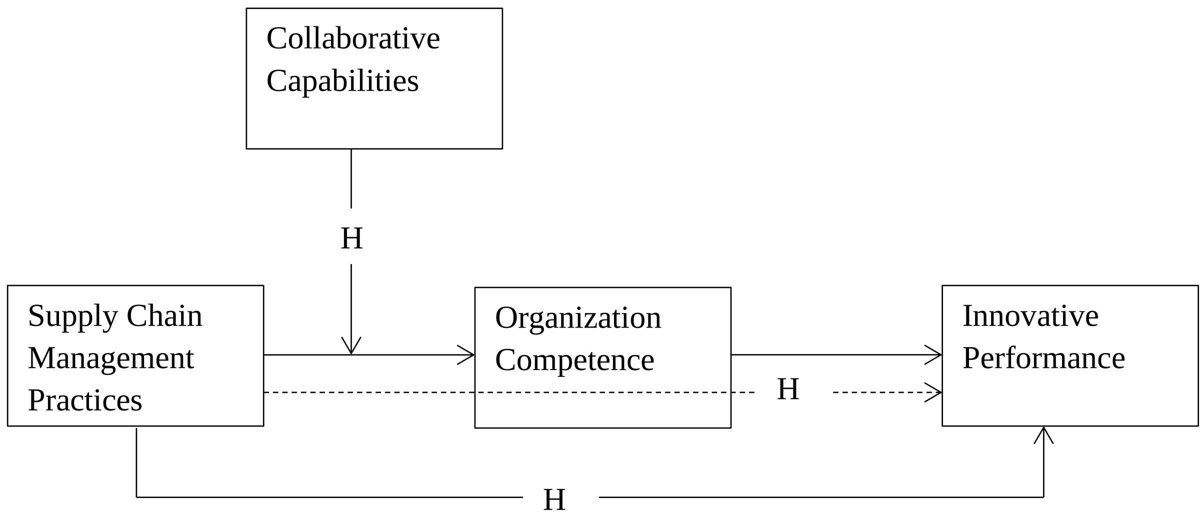

Fig. 1. Research Diagram of Study
Note: In the above model, the straight line from IV to DV represents H1, the dotted line represents H2, and the moderation represents H3.

MATERIAL AND METHODS

Data Collection and Sample

Data were collected from SMEs in Pakistan. SMEs across Pakistan fall into three major categories: manufacturing, trading, and service-related operations. We selected SMEs since they represent the majority of businesses in the country. The State Bank of Pakistan uses sales volume and number of employees as a basis on which to define a business category as a small or medium enterprise. In our sample, we selected firms with average sales ranging from Rs.50 million to Rs.800.00 million and with an average number of employees of less than 250.

Data were collected from employees working in SMEs in Punjab province, using a self-administered questionnaire comprising 32 items. We distributed questionnaires to 280 respondents, of which 201 questionnaires were found to be usable, resulting in an effective response rate of 71%. We ensured voluntary participation and also guaranteed the anonymity of the respondents and their responses. Data insights revealed that 43% of the respondents were from the manufacturing sector, 33% were from trading, and 27% were from the services sector. 53% of participants were from sole proprietorships, whereas 35% were from partnerships and 12% were from registered companies. Regarding the number of employees in firms selected for the study, 16% had 1-50 employees, 15.4% had 51-100 employees, 25.4% had 101-150 employees, 20.9% had 151-200 employees, and the remaining 21.9% had employees 201-250. This means that the sample was representative, since the employees were from all types of SMEs across the region.

Measures

Supply Chain Management Practices: SCM practices were measured by using the Koh et al. [2007] scale. The respondents reported to what extent they generally agree or disagree with a list of 12 supply chain management practices that are practised by SME firms. This used a Likert scale with options from 1 to 5 "strongly disagree" to "strongly agree". The Cronbach's alpha reliability of the scale was 0.89.

Innovative Performance: For measurement of innovative performance, scale of Thorgren et al. [2009] has been used which comprised of 5 items, each of which offered five answer options ranging from 1 "strongly disagree" to 5 "strongly agree. The Cronbach's alpha reliability of the scale was 0.81.

Organizational Competence: Organizational Competence was measured by using King et al.'s [2001] scale, which comprised 7 items, each of which offered five answer options ranging from 1 "strongly disagree" to 5 "strongly agree". The Cronbach's alpha reliability of the scale was 0.70.

Collaborative Capabilities: For collaborative capabilities, the scale developed by Kotabe et al. [2003], Koufteros et al. [2007] and Patnayakuni et al. [2006] was used, which comprised 8 items ranging from 1 "strongly disagree" to 5 "strongly agree". The Cronbach's alpha reliability of the scale was 0.88.

Control Variables: One-way ANOVA was used to identify the control variables. However, the results showed that there were no significant differences across the demographic variables, such as legal structure of business, numbers of years in business, numbers of employees and type of business. Hence, none of the demographics was controlled. The results of one-way ANOVA are shown in Table 1.

Table 1. One-Way ANOVA

Innovative Performance		
Source of variation	F	P
Legal Structure of business	2.227	0.111
No. of years in business	1.446	0.220
Type of business	1.30	0.325
Total no. of employees in business	0.257	0.905

RESULTS

Descriptive Statistics and Correlation Analysis

Table 2 represents means, standard deviation and bivariate correlations. The results show that the supply chain management practices are positively and significantly correlated with innovative performance in the organization ($r = 0.638$, $p < 0.000$), as well as organizational competence ($r = 0.212$, $p < 0.000$). Similarly, supply chain management practices showed a positive and significant relationship with collaborative capabilities ($r = 0.394$, $p < 0.000$).

Table 2. Descriptive Statistics, correlations and reliabilities

		Mean	S.D	1	2	3	4
1.	**Innovative Performance**	4.048	0.478	(0.808)			
2.	**Organizational Competence**	4.202	0.284	.307*	(0.70)		
3.	**Collaborative Capabilities**	4.181	0.512	.373*	*.329	(0.875)	
4.	**Supply Chain Management Practices**	4.060	0.424	.638*	.212*	.394*	(0.890)

**P≤0.05 n=201, Alpha reliabilities are in parenthesis.*

Regression Analysis

Direct and in-direct effects were checked by using a bootstrapping technique [Hayes and Sacharkow 2013] through SPSS process macros model 4. Table 3 shows the results for both direct and indirect paths. The direct path model provides the results for H1 in the study, which predicted a positive relationship between supply chain management practices and innovative performance. The results provide support for supply chain management practices and innovative performance (β = 0.68, p < 0.001) leading to acceptance of H1. The in-direct path model provides support for H2, which proposed that SCM practices lead to innovative performance through organizational competence. Our results provide support for the indirect path, showing that SCM practices influence innovative performance of a firm through organizational competence (β = 0.04, p < 0.001). These results give support to H2.

Table 3. Direct and indirect path coefficients

Path		Estimate	SE			Decision
H1	SCM Practices → IP	0.68****	0.06			Accepted
	Bootstrap results for indirect effects					
Path		**Effects**	**SE**	**LL 99%CI**	**UL 99%CI**	
H2	SCM Practices → OC → IP	0.04	0.02	0.01	0.13	Accepted

n = 201. Bootstrap sample size = 5,000. ∗∗∗p ≤ 0.001, ∗∗p ≤ 0.01, ∗p ≤ 0.05. SMP = Supply Chain Management Practices; OC = Organizational Competence; IP = Innovative Performance; LL, lower limit; CI, confidence interval; UL, upper limit.

Table 4 represents the results for the moderation analysis. Hypothesis 3 proposes the moderating role of collaborative capabilities between supply chain management practices and organizational competence. The moderating role of collaborative capabilities was tested using the Hayes Process Macros model 1. The results reveal that collaborative capabilities significantly moderate the relationship between supply chain management practices and organizational competence (β = 0.21, p < 0.001, CI [0.04,037], 1R 2 = 0.5), leading to acceptance of hypothesis 3.

Table 4. Moderating role of Collaborative Capabilities (DV: Organizational Competence)

	B	SE	LLCI	ULCI	Decision
Constant	4.19	0.02	4.13	4.24	
SCM Practices	0.13	0.050	-0.01	0.27	
CC	0.16***	0.04	0.06	0.26	
Interaction	0.21***	0.064	0.04	0.37	Accepted
ΔR^2 due to Interaction	0.05***				
Slope Test					
Moderator: CC					
-0.51	0.03	0.05	-0.09	0.15	
0.00	0.13	0.05	-0.00	0.27	
0.51	0.24	0.07	0.06	0.43	

n= 201. SCM Practices = Supply Chain Management Practices; OC = Organizational Competence; CC= Collaborative capabilities, Bootstrap sample size = 5,000. LL, lower limit; CI, confidence interval; UL, upper limit. ∗p ≤ 0.05, ∗∗p ≤ 0.01, ∗∗∗p ≤ 0.001.

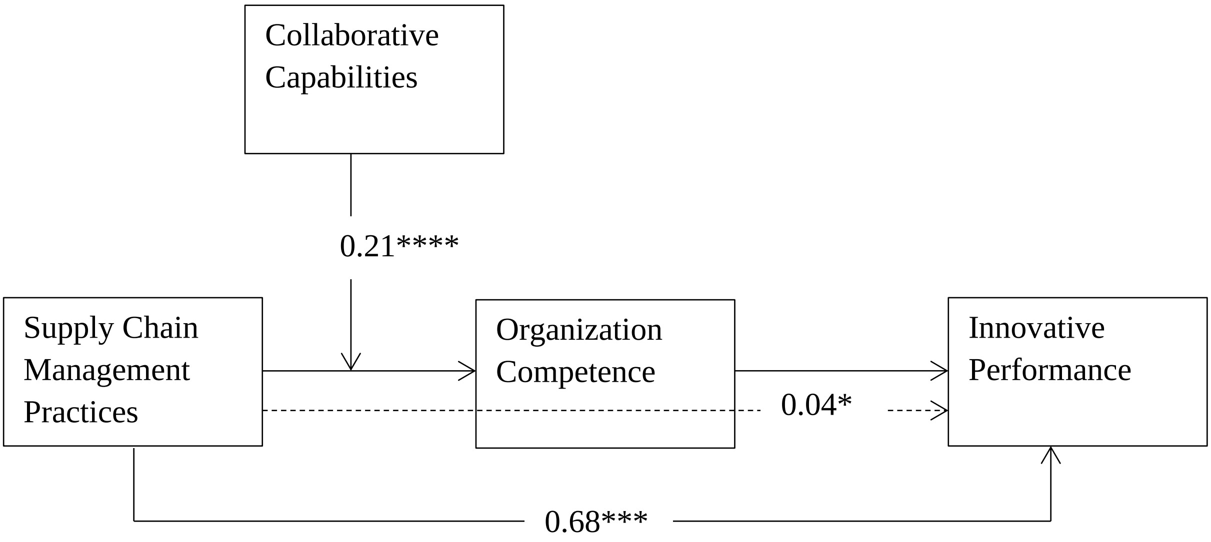

Fig. 2. Results of the Study

In the above figure, the beta values for each relationship are shown along with the significance level. Likewise, since the interactive term is positive, the relationship between supply chain management practices and organization competence is depicted through a slope diagram at a different level of collaborative capabilities.

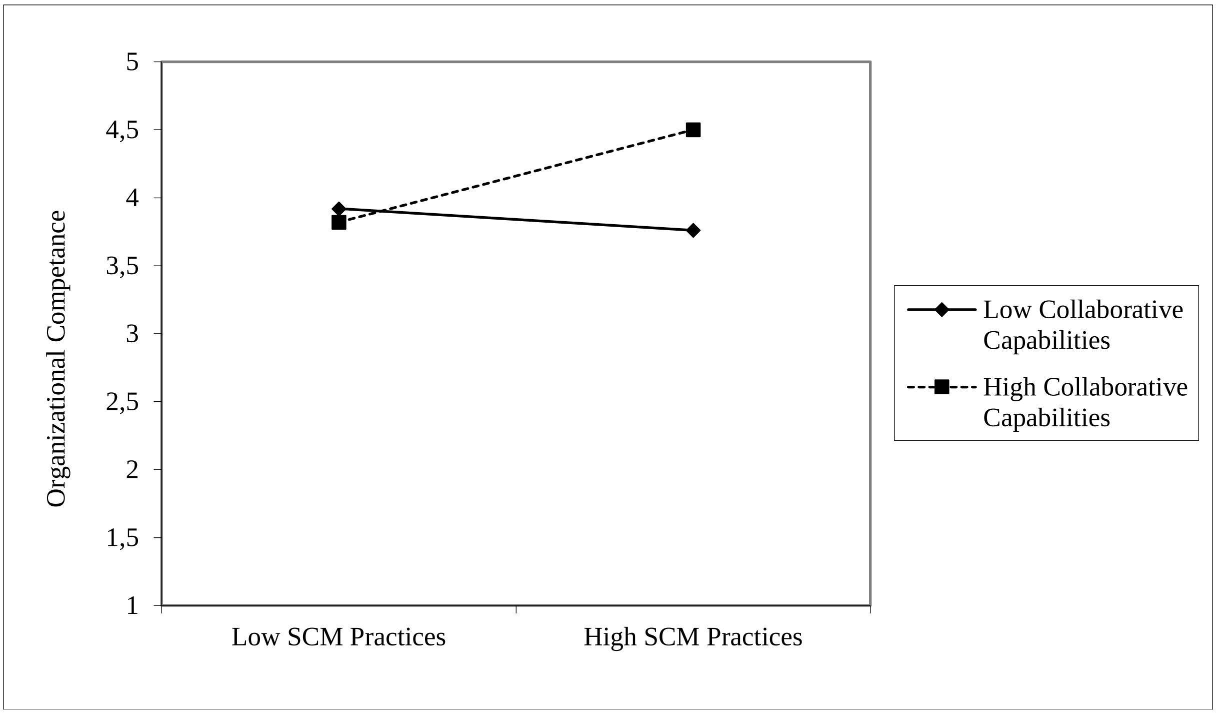

Fig. 3. Interaction Plot, SCM Practices = Supply Chain Management Practices, OC = Organizational Competence

The interaction plot shown in Figure 3 illustrates how the interaction for SCM practices is stronger when collaborative capabilities are high ($\beta = 0.24$, $p < 0.001$), while it is insignificant when collaborative capabilities are low w ($\beta = 0.05$, p = n.s.). These results provide support for our moderation hypothesis.

DISCUSSION

By integrating SCM practices, organizational competence, collaborative capabilities and innovative performance, we found evidence for both direct and indirect results. Our findings indicate that organizational competence partially mediates the relationship between SCM practices and innovative performance. Our results also show that firms with collaborative capabilities can improve their organizational competence by implementing SCM practices.

Our findings are in line with previous studies which show that the implementation of SCM practices helps firms to bring about innovation in their products, services, and operations [Zeng et al., 2010, Kaminski et al., 2008, Dolereoux, 2004]. Hence, the findings of this study further validate existing literature pertaining to the existence of a positive relationship between SCM practices and innovative performance. SCM practices, including handling customer relationships, real-time sharing of information, and strategies to effectively engage business partners, are very important for the success of any organization [Afraz et al., 2021]. Organizations that ensure the coordination and configuration of the processes necessary for the timely distribution and availability of their products and services can enjoy innovation in their products. Strategic planning, customer relationship, information sharing and information quality can promote organizational effectiveness [Koh et al., 2007], which ultimately leads to innovative performance.

Our results also provide support for the mediating role of organizational competence between SCM practices and innovative performance. In the past, researchers have found a significant relationship between SCM practices and organizational competence [Tippins and Sohi, 2003]. Organizational competence based on sales and profit growth, customer retention and return on investment can bring about innovation in a company's products and services.

Furthermore, the current study addresses the moderating role of collaborative capabilities between SCM practices and organizational competence. Collaborative capabilities help the firms to effectively engage all stakeholders of a business in which communication becomes stronger and updated information is shared in real time, which ultimately improves organizational competence, especially in the financial aspects of organizational competence, such as inventory, logistic and other related information. All these activities minimize the losses and maximize profitability, leading the firm to enjoy a competitive advantage. According to the resource-based view of firms, resources and capabilities together lead the firm towards a competitive advantage [Huo 2012]. When organizations implement SCM practices and have high collaborative capabilities in terms of sharing information, setting performance goals, making decisions jointly, and sharing business resources, these capabilities with SCM practices lead the organizations towards competence.

Practical Implications

The current study has several implications for managers and policy makers. The findings are helpful for organizations in terms of implementation of SCM practices. When organizations integrate and coordinate their activities according to the demands of the customers, these activities will improve the organizational competence, which ultimately boost innovative performance. Although integrating supply chain activities is a major challenge for managers, it improves an organization's innovative performance. Innovation is a continuous process, which gives competitive advantages to firms. Moreover, at present, business environments where fast and innovative solutions to existing problems are imperative for business growth, supply chain management practices provide room for improvement and innovation. This study further recommends that to achieve a competitive advantage in the market and across the world, SME firms should implement supply chain management practices in a more effective and efficient way, as these practices are helpful in solving many practical problems faced by many operating businesses. Furthermore, collaborative capabilities are a very important part of SMEs because these capabilities help to improve the organizational competence in the presence of SCM practices.

Limitations and Future Research Directions

Despite many practical implications, this study is not without limitations. Firstly, it only focuses on SMEs, which may limit the generalizability of the results, because SMC practices can vary from sector to sector, as well as from supply chain to supply chain [Aslam et al., 2021]. Therefore, it is important to replicate this model in other industries to increase the generalizability of the findings. Secondly, a survey-based study design with closed-ended questions was used, which itself has the limitation of not capturing additional explanations and in-depth information. It is recommended that future researchers should conduct qualitative case-based studies to gain in-depth information, which may lead to practical solutions to many research questions.

Another limitation is the small sample size and cross-sectional data. Future researchers are therefore recommended to increase the sample size for better results and revalidate the research findings. In addition, a longitudinal study design is also recommended, which may help the researchers to access change at different points in time and to establish cause and effect relationships [Isnaini et al., 2020]. Although the study tried to capture data from SME firms operating across Pakistan using the convenience sampling technique, SMEs availing facilities from banking channels were taken into the sample, which limits the generalizability of findings to the entire SME sector operating in Pakistan. Finally, as this study focused only on SMEs operating in Pakistan, its findings are not applicable to all SMEs operating in developing countries. In future, more research in this field would help to validate the findings of our study.

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ORIGINAL PAPER

DIGITAL TWINS FOR SUSTAINABILITY PURPOSES IN LOGISTICS INDUSTRY: A LITERATURE REVIEW

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ABSTRACT. Background: The concept of digital twins has been gaining popularity in various industries due to its potential to enhance performance, optimise operations, and reduce costs. Digital twins have shown promising results in improving sustainability in the logistics industry by providing a virtual replica of the logistics activities, processes, systems, equipment or machinery, enabling real-time monitoring, promoting collaboration, and integrating with other technologies. Digital twins can, among others, reduce, optimise, and minimise various costs in logistics activities. This paper's purpose was to explore and analyse the current state of research literature on the implementation of digital twins in logistics for sustainability purposes.

Methods: The paper utilises a structured bibliometrics and systematic literature review methodology to answer these questions and follows the PRISMA methodology. Scopus and Web of Science were used to identify previous research on this topic with the search string (sustainab* AND logistic* AND "digital twin*"). Research that included theoretical or practical digital twin applications for increasing logistics' sustainability was analysed from a basic bibliometrics viewpoint and then systematically reviewed to determine and interpret the significance of digital twins' implementation for the sustainability of the logistics industry. An emphasis was given to the means of digital twin implementation, its scope, and the sustainability aspects (environmental, social, and economic) that the research and consequent implementations target.

Results: The main goal was to identify how scientific literature views the potential impact of digital twins on the sustainable development of the logistics industry and to acquaint the reader with a coherent collection of relevant research from the researched field. Among 47 documents, only 18 met the inclusion criteria for further bibliometrics and content analysis. Unfortunately, only a few publications directly presented digital twins' use for increasing sustainable aspects of logistics activities.

Conclusions: The number of publications regarding digital twins in logistics is increasing, but to a large extent they are not concerned with practical implementation. The latter testifies to the degree and extent of literature on digital twins' integration and implementation for sustainability in the logistics industry still being scarce.

Keywords: digital twins, logistics industry, sustainability, sustainable aspects, systematic review

INTRODUCTION

Digital twins are data-based digital models of physical objects [Minerva et al. 2020], processes [Tao and Qi 2019], or systems [Hartmann and Van der Auweraer 2021, Stark et al. 2019] that enable simulations [Barykin et al. 2020] in a virtual environment [Defraeye et al. 2021]. Through logistics, they can be implemented in four constant multitudes of supply chains: products, services, processes, and/or systems [Kajba, Jereb and Obrecht 2023].

Digital Twin technology has been known about for two decades. Nevertheless, its implementation is relatively new in the logistics field [Moshood et al. 2021] and supply chain systems [Kajba, Jereb and Obrecht 2023]. Digital twins enable (a) insight into the past, (b) optimisation of the present, and (c) innovation of future performance through implementation into products, services, machines, processes, systems, and even entire business ecosystems [Lu et al. 2019]. Premised on the latter, their use brings vital benefits that affect the sustainability aspect of logistics operations and achieving

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sustainability goals that include environmental, social, and economic aspects. Thus, further research into this subject matter is crucial to achieving developments and innovations in sustainable logistics operations.

Theoretical background

Digital twins, artificial intelligence, the Internet of Things (IoT), and cloud computing represent a few Industry 4.0 tools that support technological revolution towards accelerated efforts of cyber-physical operations', services' and systems' efficiency optimisation [Akkad et al. 2022]. The consecutive development of sensor technologies, IoT, and big data analytics has led to the inevitable advancement of digital twins, which enable the interlacement of the physical and digital worlds [Tao et al. 2019].

Digital twins are usually presented as three-dimensional replicas of physical objects or systems, where they use real-time data obtained from sensors that monitor the studied objects' or systems' performance, their environment, or even similar digital twins [Barata et al. 2020]. In simple terms, it can be said that the digital twin operates based on mirroring the life of its corresponding physical twin through an integrated multi-physics, multi-scale probabilistic simulation of the physical counterpart [Glaessgen and Stargel 2012]. However, a digital twin is more than just a digital representation or a replica of the physical object [Belfadel et al. 2021] – it is a comprehensive physical and functional representation of the object under study, where all the necessary information within the life cycle for proper processing is provided [Boschert and Rosen 2016]. Dynamic correspondence connects the digital twin platform with models and data, enabling monitoring and synchronising the current state and behaviour of the digital twin with the mirrored physical environment. However, this connection is generally one-way oriented – from the physical world to the digital replicas, which are considered the digital shadow [Kritzinger et al. 2018]. This will be discussed further in a future paper.

A more adept explanation of digital twins' follows. Technology enablers for digital twin construction include modelling, predictive analytics and decision-making methods correlated with lifecycle data, and targeted knowledge with real-time historical and operational data [Belfadel et al. 2023]. A cyber-physical system combines physical devices correlated in virtual cyberspace, using a data transmission network. Each physical device has its cybernetic component, which represents a digital image of the device in question – the latter catalyses digital twin models. The digital twin can thus inspect and control the physical entity in question and transfer data to optimise and integrate the virtual model. The digital twin model represents an exact and current cyber counterpart of a physical product, process or system that adequately reflects all its functionalities, assimilates extensive contextual work data, and is used as infrastructure for planning, network upgrading, and rapid transformation. In contrast to standard simulation design, the digital twin component is not only a visual reproduction of contingencies or a means of reporting results but also a validation tool for a complete lifecycle upgrade solution. [Andronie et al. 2021]

It should be noted that digital twins are not identical twins. The notion of an exact replica is only an idealisation and an aspiration that may never even be achieved [Batty 2018]. In addition, the studied object must be characterised by evolving data, as physical conditions change in parallel with time. Therefore, decisions must be based on evolving data collections rather than the data collections of a time interval, which provides only a snapshot of the situation at the given moment. This way, it is possible to better understand systemic changes over longer time intervals and patterns. And just like datasets, digital twins depend upon dynamic updates associated with simulation models, which evolve based on physical conditions. [Kaur et al. 2020]

Quite a few contributions can be found in the literature in the context of implementing Industry 4.0 tools. Digital twins have been recently acknowledged for support in advanced experimentation, simulation, and decision-making for on-demand logistics operations [Belfadel et al. 2023]. Nonetheless, digital twin frameworks are still being mainly implemented in the context of producing, manufacturing, and shop floor management [Haße et al. 2019, Zhuang et al. 2018], but it is clear that the existing architectures are too universal to be used in logistics [Haße et al. 2019]. Nevertheless, concrete use cases for implementing such architectures are rare in logistics, even though digital twins' implementation offers significant added value [Hopkins and Hawking 2018].

Logistics facilities can be equipped with comprehensive sensor systems, based on which a digital image of an individual logistics entity is created, which represents a digital twin. [Wohlfeld 2019]. Digital twins facilitate communication between assets, objects, processes, and various systems [Belfadel et al. 2021], while its architecture facilitates the analysis and processing of extensive data collections in real-time [Haße et al. 2019]. Besides data management, digital twins enable behaviour simulations of the studied object or complement the physical object with digital services. Depending on the digital twins' build requirements, the latter includes a three-dimensional build model, structural properties information, component manufacturer information, maintenance intervals information, and other crucial or necessary information. [Gehring and Rüppel 2023] The challenge in digital twins' creation is in the appropriate data structure design, the required data collection and integration, and the appropriate interface creation to use this data [Tao et al. 2019]. Data collection is not the main challenge in logistics – the decisive factor is how this data is processed further to facilitate maximum added value [Belfadel et al. 2021].

Sustainable development of supply chains is based on environmental, societal, and governance aspects [Zhang et al. 2023]. The abbreviation ESG stands for 'E'nvironmental impact of business activities; 'S'ociety deals with, e.g., employee benefits or product liability; and 'G'overnance focuses on corporate norms and risk management [Díaz et al. 2021]. Digital twin technology represents one of the most promising tools for Industry 4.0 realisation [Tao et al. 2019] whilst enabling sustainable performance improvement [Kaewunruen and Lian 2019]. Many authors have researched the usage and/or implementation of digital twins in logistics for sustainable purposes, such as:

- for accuracy and efficiency improvement of sustainable material selection for laptop design [Xiang et al. 2019];
- for sustainable intelligent manufacturing [He and Bai 2021];
- achieving sustainable objectives in the supply chain, such as prediction of operational failures, improvement of product quality, and reduction of downtime [Kamble et al. 2022];
- for obtaining and predicting the information on performance, energy consumption, and costs from the virtual space through simulations [Zhang et al. 2023].

The constantly evolving technology of digital twins thus represents an innovative and competitive solution for providing sustainable logistics services. With the help of IoT, digital twins provide traceability for sustainable logistics [Yang et al. 2022], which emphatically influences a company's sustainability performance [Zhou et al. 2021]. Logistics is a widely dispersed area where there are many opportunities for digital twin implementation, for example, from sustainability evaluation of companies based on ESG [X. Liu et al. 2021], sustainable urban road planning [Jiang et al. 2021], secure information management [Putz et al. 2021], sustainable blockchain-enabled supply chain [Mukherjee et al. 2021], sustainable smart city design [Xia et al. 2022], and many others.

Therefore, the use of digital twins in logistics contributes to a more sustainable operation of logistics systems, as it can reduce the negative impact on the environment, improve the working conditions, and increase the efficiency and competitiveness of the company. Furthermore, it contributes to sustainable development, which is positively perceived by the environment, society, and governance bodies (ESG). Collectively, the use of digital twin technology is important to achieving sustainability objectives in logistics, as it enables better planning and more efficient operations, consequently improving the environmental, social, and economic aspects of logistics operations.

Scope, objectives, and aim

This paper explores how digital twins can enable more sustainable logistics operations. The latter will be done through structured bibliometrics and systematic literature review methodology, where two literature databases (Scopus, Web of Science) will be used to identify research on this topic and obtain suitable literature for further analysis.

Literature that includes theoretical or practical digital twin applications for increasing logistics' sustainability is first analysed from a basic bibliometrics viewpoint. Afterwards, the suitable literature is systematically reviewed to determine and interpret the significance of digital twins' implementation for the sustainability of the logistics industry. An emphasis will be given to the means of digital twin implementation, its scope, and the sustainability aspects (environmental, social, and economic).

The main objectives are:

- to identify how scientific literature views the potential impact of digital twins on the sustainable development of the logistics industry;
- to divide the suitable scientific literature into three sustainability sections: environmental, social, and economic. The latter is based on the digital twins' implementation for enabling sustainability in logistics through the codification process;
- to acquaint the reader with a coherent collection of relevant research from the researched field.

This paper aims to broaden the understanding of digital twins' implementation in logistics, focusing on sustainability aspects. Essentially, the idea of this paper was premised on previous research, where bibliometrics and literature review were conducted for digital twins implementation in transport and energy fields since "transport has an enormous impact on the sustainability of supply chains, which is emphasised through the close correlation between environmental and economic aspects" [Kajba, Jereb and Cvahte Ojsteršek 2023]. The difference emerges in the studied field, which is logistics rather than supply chains, and was encouraged by another study that considered IT trends for modelling investments in supply chains by prioritising digital twins [Kajba, Jereb and Obrecht 2023]. Here, a further examination of the benefits, challenges, and impacts of digital twin technology implementation in logistics was proposed.

Thus, this paper touches upon a crucial topic in today's world: the degree and extent of literature on the integration and implementation of digital twins for sustainability in the logistics sector, where the paper's main contribution can be found in the bibliometric and systematic overview of the respective topic.

METHODOLOGY

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were applied in reporting the procedure and analysis of the presented literature pool where applicable [Page et al. 2021].

Publication search and selection

Web of Science and Scopus were selected as databases for preparing a literature pool for the review since these two databases are recognised as the leading compilations of academic documents [Zhu and Liu 2020]. Web of Science and Scopus have significant overlaps in coverage but vary in some aspects that make using both in the starting phases of literature reviews feasible [Echchakoui 2020, Okagbue et al. 2020]. A Web of Science search in July 2023 returned 30 documents, while the Scopus search with the input parameters of (sustainab* AND logistic* AND "digital twin*") returned 49 documents. After removing duplicates and entries that are not scientific publications, the whole literature pool included 47 individual documents. Two authors scanned the titles and abstracts of the eligible publications to determine whether they were suitable for inclusion in the final literature pool. In cases of disparities between the authors' decisions and where the decision could not be made based on abstracts alone, the whole documents were obtained and checked. The third author was included to make the final verdict for the documents where an inclusion decision could not be made. Overall, 18 documents were included in the literature pool after the abstract and publications review. The inclusion criteria were as follows:

- the documents present a journal or conference paper or a book or a part of a book (e.g., patents, datasets, software, or methodological explanations were excluded);
- there were no limitations as to the publication year or source;
- the document explicitly addresses at least some aspects of sustainability (e.g., documents that only mention the potential to reduce carbon footprint as part of the final discussion but do not explicitly address it in the research part were excluded);
- the document explicitly addresses digital twin use from a practical or theoretical standpoint in the research part of the contents;
- the research is focused on logistics or at least a subset of logistics activities (i.e., transport, warehousing, city logistics, etc.).

All 18 publications were available in the Scopus base, representing the source for bibliographical information used in the bibliometrics and content analysis. The research methodology process for publication search and further analysis is evident in Figure 1.

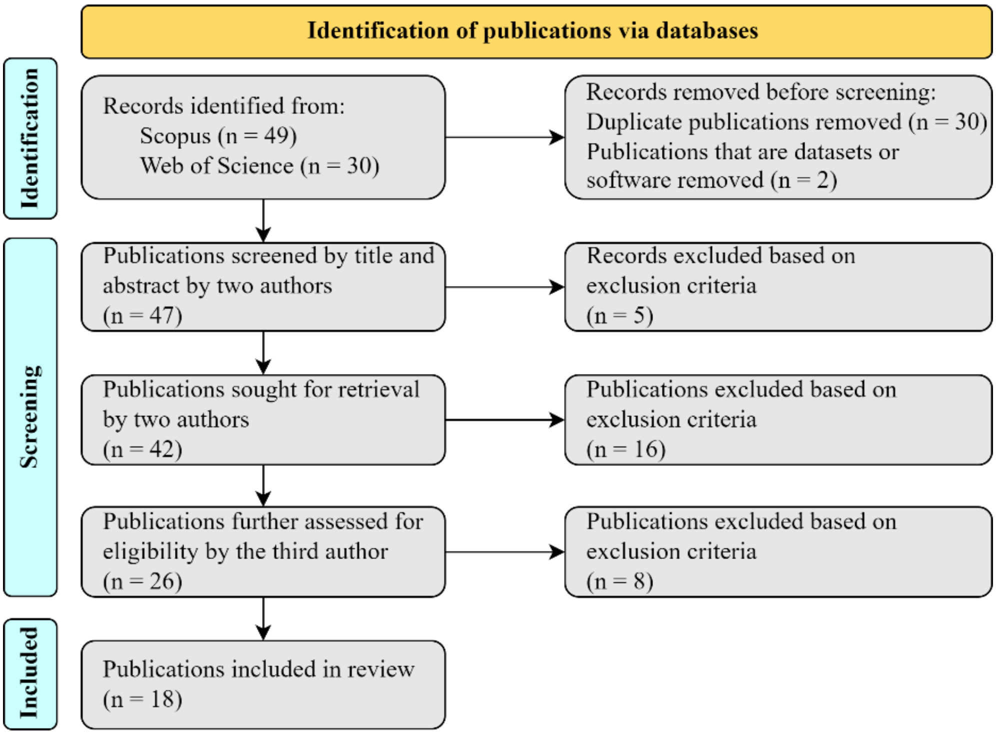

Fig. 1. The research methodology process.
Source: own.

Bibliometric analysis

Bibliometric analysis comprised a descriptive analysis of publication year, sources, and origin countries. Data for these were taken from the bibliographical publication data from Scopus.

Further analysis focused on keywords the authors assigned to their publications and index keywords from Scopus. VOSviewer [van Eck and Waltman 2014] was used to perform a co-citation analysis for the whole pool of keywords to determine which topics are most prominent in researching sustainability and the potential for digital twin use in logistics. Author and index keywords were exported from Scopus for the included 18 publications. Altogether, this gave a pool of 351 keywords. They were scanned for duplicates and synonyms, and a thesaurus was prepared for use in VOSviewer that enabled the software to combine keywords written differently but sharing a common meaning. E.g., the keywords "supply chain", "supply chains", and "supply chain management" were joined into one keyword group with the name "supply chain management" and were consequently considered by VOSviewer as one keyword. This left 195 keywords to be included in the co-occurrence analysis. Co-occurrence denotes an occurrence of two keywords in a paper, and bibliographic analysis of co-occurrence shows the interconnectedness of keywords in the literature pool, which consequently points to the overarching themes that appear in the analysed literature. VOSviewer prepares a clustering of keywords based on the network of used keywords in the publication pool regarding usage and occurrence in shared publications. The clustering was also a basis for determining the most prevalent topics and publication areas in the researched field.

Content analysis

The publications in the literature pool were analysed in accordance with the research objectives. Firstly, the contents were analysed in accordance with the field of logistics application, sustainable aspects that the presented research considers (environmental, social, economic), the scope of digital twin implementation, and the constant multitudes of supply chain systems [Kajba, Jereb and Obrecht 2023]. Based on the codification of research contents, an in-depth content analysis focused on how digital twins were used in the publications from the literature pool to enable more sustainable logistics operations.

RESULTS

The results present a detailed analysis of publications up to July 2023 that deal with digital twins to increase sustainability in logistics operations. Interestingly, authors frequently seem to think of the sustainability aspect as an umbrella concept but fail to acknowledge how their research results contribute to sustainable logistics operations, e.g., [Trebuna et al. 2022], or sustainability is mentioned as an advantage of digital twin implementation without further explanation [Lam et al. 2023]. Publications like these were excluded from the analysed literature pool due to the lack of focus on the intended fields.

Bibliometric analysis results

In terms of publication years, the first year in which the covered topics appear is 2019, with two publications, and 2020 also follows with two publications. 2021 produced seven publications, 2022 five publications, and two were published in 2023 so far (Figure 2).

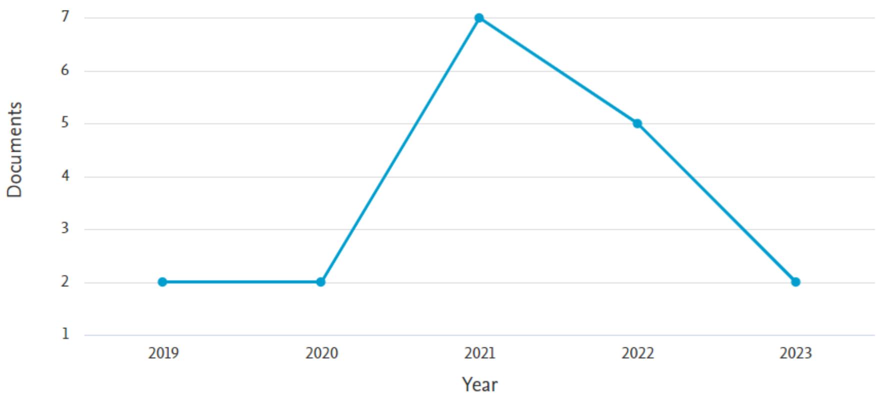

Fig. 2. Quantity of published publications on the topic between 2019 and 2023.
Source: own work.

Regarding author affiliations, China, France, Hungary, and Italy are the most productive countries. Overall, 20 unique countries contributed to the literature pool. Countries with at least two publications are shown in the graph below (Figure 3).

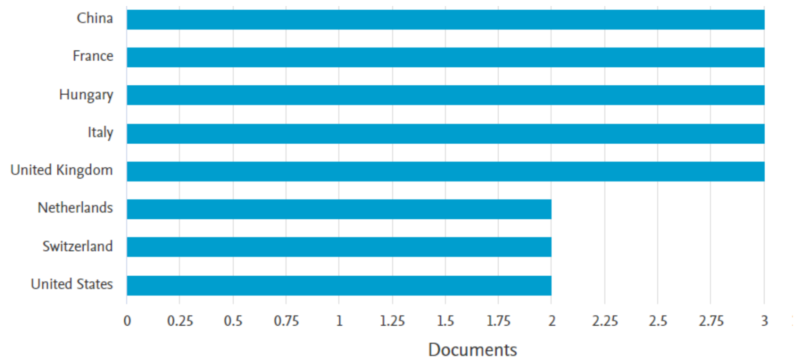

Fig. 3. Quantity of published publications by countries.
Source: own work.

Regarding the publication type, 11 publications are journal articles, and 7 are conference papers. The only source that stands out with three publications in the literature pool is the Journal of Cleaner Production with three publications. In contrast, other sources are unique and have only published one publication in our literature pool.

A deeper analysis of citations and co-citations was hindered by the small number of publications in the literature pool and the relatively young field of research. Therefore, further research into co-citations and coupling was not performed.

Keyword analysis was performed to determine the most prevalent topics in the literature pool. If we set the minimum number of occurrences for a single keyword to 5, only 5 keywords would meet the inclusion criteria – these are "digital twin", "sustainable development", "production logistics", "supply chain management", and "sustainability" – the keywords that are guided by our research objectives. To broaden the scope of keyword co-occurrence analysis, the minimum number of occurrences of a keyword in the literature pool was set to two occurrences among the author and index keywords, which returned 35 unique keywords. The co-occurrence matrix of the keyword pool is shown in Figure 4.

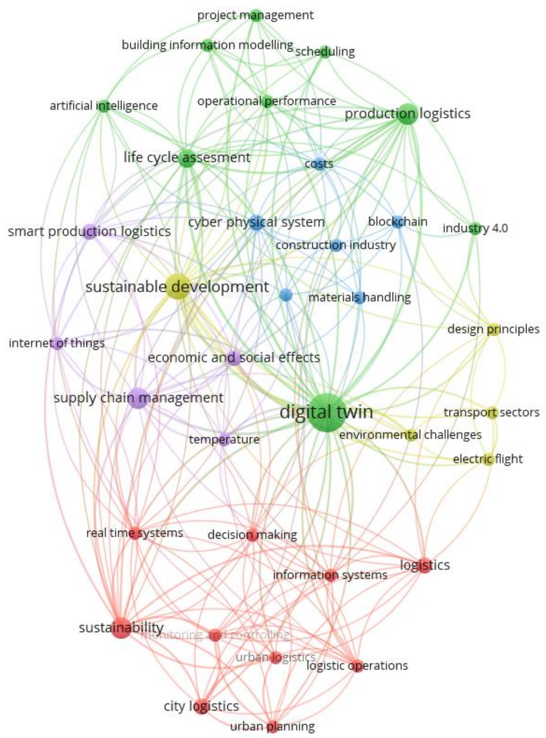

Fig. 4. Co-occurrence matrix of the keyword pool.
Source: own work.

The co-occurrence analysis identified five topical clusters. The green cluster is connected mainly to Industry 4.0 and production logistics with operational performance and project management. The red cluster is focused more on logistics as a holistic topic connected to decision-making and planning. The purple cluster is centred on supply chain management and its economic and social effects with the addition of contemporary technologies such as IoT and smart systems. The yellow cluster is transport-oriented, with an additional focus on sustainable development from an environmental perspective. The blue cluster focuses on digital twins as cyber-physical systems mainly concerning construction and materials handling.

Content analysis results

Since the main focal point of the research is enabling more sustainable logistics, an analysis of which logistics and sustainability aspects are most often covered in the literature from the field was made first. In terms of logistics areas, transport and construction logistics were the predominant fields, with five publications each (Table 1).

Table 1. Quantity of publications regarding application in the logistics field

Field of logistics application	Number of publications
Transport	5
Construction logistics	5
City logistics	3
Production logistics	3
Medical logistics	1
Supply chain management	1

Source: own work.

According to the considered sustainability aspects, the publications were assigned into different groups: environmental, social, and economic. Due to the specifics, one publication can be included in more than one group if it covers more than one field of sustainability (Figure 5). Most publications focused on the environmental aspects of sustainability, often through reducing emissions and energy consumption (e.g. [Akkad et al. 2022] and [Portapas et al. 2021]). Social and economic sustainability were less predominant.

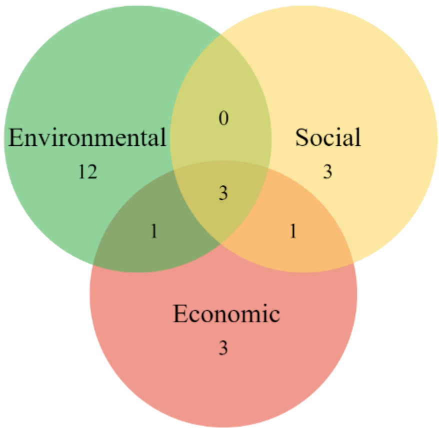

Fig. 5. Quantity of publications regarding sustainability aspects.
Source: own work.

Three publications deal with all three aspects of sustainability as a result of digital twin applications. [Ruperto and Strappini 2021] uses a digital twin of a construction project to overcome the potential logistics and sustainability issues in constructing an office building. Its main goal is to monitor the construction process of the building, ensuring adequate information flows, efficiency, and cost-effectiveness. [Kim et al. 2021] designed a laboratory case study of a digital twin for an automotive manufacturing company that focuses on internal order picking and transport processes. They show that using digital twins for real-time scheduling optimisations based on cyber-physical connections can contribute to all three aspects of the sustainability of an intralogistics process. [Kamble et al. 2022] presents an implementation framework for digital twins in manufacturing supply chains, based on a literature review, as well as the potential for their use in increasing the sustainability of supply chains.

According to the level of digital twin implementation, the publications vary from a conceptual framework to actual implementation descriptions. Consequently, the publications were divided into several groups:

- Conceptual frameworks are publications where the digital twin is described, the basic model or architecture is given, and sometimes even some technical solutions, but no implementation is shown.
- A step further is a use case, where the conceptual framework is also applied to a theoretical or concrete case, but only in terms of a general implementation idea or laboratory experiments.
- The final step in terms of concrete use is an implementation case study, where the developed digital twin is used in practice, and the concrete outcomes are presented in the publication.

Based on this, the publications were divided by implementation level, as shown in Table 2 below. The three most developed publications that address actual implementation cases cover different aspects of sustainability. [Accorsi et al. 2022] used a tailored digital twin to improve the spatial life cycle assessment of secondary food packaging use. They modelled a large-scale transport network and connected it to emissions and fuel consumption in connection to material flows, then used it to determine the environmental impacts of using different reusable plastic containers in comparison to single-use containers. Their concrete results support increased environmental sustainability in logistics through reduced transport emissions and container production and disposal impacts. [Pilati et al. 2021] used a digital twin of a mass vaccination centre for real-time mapping and optimising operator and queue flows. Their results allowed for optimising vaccination efficiency, reducing queues of patients, and resource allocation and optimisation. This contributed towards improving the logistical operation's economic and social sustainability aspects. [Zhao et al. 2022] focuses on economic aspects of sustainable production logistics through utilising IoT devices on mobile resources in the manufacturing system in connection to a digital twin to optimise resource allocation in real-time.

Table 2. Quantity of publications regarding digital twins' implementation level

Digital twin implementation level	Number of publications
Conceptual framework	6
Use case	9
Implementation case study	3

Source: own work.

A part of researching supply chains and logistics is defining the constant multitudes of supply chain systems: products, services, processes, and systems. These present "a consistent part of any and every supply chain system"; furthermore, in themselves, they "form a multitude of other products, services, processes, or systems", which are intercorrelated [Kajba, Jereb and Obrecht 2023] (Table 3).

Table 3. Quantity of publications, divided into constant multitudes of supply chain

Constant multitudes of supply chain systems	Number of publications
Products	2
Services	1
Processes	8
Systems	7

Source: own work.

DISCUSSION

Digital twin use is recommended as a tool for increasing the sustainability of operations in, e.g., freight transport [Dwivedi et al. 2022] and specifically urban freight transport [Golinska-Dawson and Sethanan 2023]; however, both of these publications focus specifically on energy consumption and do not propose concrete roles or implementation procedures for digital twins.

Only a few publications present the use of digital twins to increase sustainable aspects of logistics activities directly. For example, Accorsi et al. [2022] applied a network analysis software-based supply chain digital twin to evaluate input parameters of a life cycle analysis and environmental impact analysis for various packaging alternatives in the food logistics field. Zhao et al. [2022] applied a digital twin to a production facility to track resources, optimise their allocation, and increase efficiency. Publications like these are scarce in today's literature, showing a sizeable potential research gap. The presented publications prove that digital twins can be successfully used in making logistics more sustainable; therefore, we can safely assume that even though the field is currently under-developed, the sole potential of the contemporary modelling and simulation techniques can and will revolutionise the way logistics stakeholders operate and interact with their environments, leading to significant advancements in efficiency, cost-effectiveness, and environmental impact reduction, as well as reducing negative social impacts. As further research and innovation continue to bridge the existing gaps, we can anticipate a future where digital twins become an integral part of strategic decision-making, enabling companies to optimise their supply chains, reduce resource consumption, and create a more sustainable and resilient global logistics network.

A significant limitation to our research is the fact that making various logistics aspects more efficient oftentimes also makes them more sustainable. Still, these effects might not have been explicitly addressed in some publications that were not included in the literature pool. E.g., Gehring and Rüppel [2023] present how using digital twins could optimise the transport and storage of materials in construction projects but does not explicitly address any sustainability factors, and Y. Liu et al. [2021] address a digital twin use case in city delivery and parking management, optimisation of which undoubtedly contributes to sustainability. Nevertheless, this aspect was not explicitly addressed in the paper. Another limitation that is derived from this notion is the search parameters that were used. As said before, many publications focus on using digital twins to improve business operations, reduce emissions, etc., but do not connect these to the broader concept of sustainability. The set search parameters did not recognise these publications as relevant to the present paper.

CONCLUSION

The paper's main contribution is as a bibliometric and systematic overview of digital twins' technology in the logistics industry to enable more sustainable operations. Of the 47 publications in total, 18 met the set criteria and were included in further analysis. With the practical implementation of digital twins' technology in logistics, the paper's first objective was fulfilled, where only three publications described actual digital twins' implementation cases in different sustainability aspects. Regarding the paper's second objective, only three papers in total touched upon all three sustainability aspects, which is a low number in retrospect. The latter testifies to the fact that the number of publications regarding digital twins in logistics is increasing, but to a large extent they are not concerned with practical implementation.

With the bibliometric and systematic overview of the topic, the third objective, and the paper's aim to broaden the understanding of digital twins' implementation in the logistics field, focusing on sustainability aspects was accomplished. This paper's purpose was to explore and analyse the current state of research literature on the implementation of digital twins in logistics industry for sustainability purposes, which was accomplished through the research. Furthermore, as seen from the results, the degree and extent of literature on integrating and implementing digital twins for sustainability in the logistics sector is still scarce. The goal is to facilitate an understanding of the logistics networks' correlations and the outcomes resulting from implementing specific innovations [Belfadel et al. 2021].

New flexible and innovative approaches in supply chain and logistics fields are needed, such as digital twins, to support experiments, simulations, and managerial decisions regarding logistics operations [Belfadel et al. 2021]. Hence, it's advisable to implement data-driven models alongside real-world experiments to predict the consequences of response actions and replicating results, where digital twins can prove valuable [Belfadel et al. 2023]. Playing a significant role, digital twins will be instrumental in forecasting future dynamics [Abideen et al. 2021] by mapping and monitoring various aspects of the supply chain system, including optimum network design, inventory management practices, supply and distribution techniques, logistics integration, outsourcing, and procurement approaches [Zhong et al. 2017].

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ORIGINAL PAPER

FUZZY PROCESS MATURITY MODEL FOR SERVICE ENTERPRISE

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ABSTRACT. Background: The purpose of this article is to present a model of process maturity assessment dedicated to service enterprises. The model developed is validated in a company in the development services sector.

Methods: The implemented research methodology includes literature analysis, expert research, fuzzy set theory, and a case study.

Results: The results indicate that the developed model provides a solid and practical diagnostic tool, based on a fuzzy index to measure the process maturity of a service company.

Conclusions: The proposed model may have practical implications for the assessment of process maturity in the service sector. It will allow a diagnosis of the current state and will indicate the direction of further improvement in process management. From an epistemological perspective, the proposed model fills the research gap in the field of maturity models dedicated to service enterprises and extends knowledge on adapting fuzzy set theory to assessing process-orientated maturity of enterprises.

The originality of the proposed approach results mainly from the research object that was used to validate the model.

Keywords: process maturity model, BPM, fuzzy assessment

INTRODUCTION

Business processes, organisations, and environments are becoming more and more complex, advanced, and continuously changing. Enterprises face numerous challenges, including the following: shifting the conditions of running a business from the model of slow and continuous changes to the model of dynamic and revolutionary ones, caused by turbulence of the environment, in which changes are taking place faster and faster, are unpredictable, and have a long, global impact (e.g., Covid-related lockdowns on a global scale); the pressure of global competition caused by interpenetration of geographic and sectoral boundaries, enabled by globalisation and e-commerce development and consequently facilitating international business operations for micro and SMEs; new distribution channels and ways of contacting customers and suppliers, resulting from IT development; changes in products and processes driven by global and counteracting trends, such as consumerism shortening of the product life cycle; ecology that sets consumer expectations regarding the quality of products and services higher and product lifecycle longer; and changes in technology and society that produce new customer needs.

All of these challenges are confronted with the need to generate profit, reduce costs, and meet customer expectations, making business more difficult and demanding.

In order to survive and grow, enterprises must demonstrate maturity. According to Hammer, maturity is the systematic improvement of organisational skills and the processes implemented in it in order to achieve higher efficiency in a specific time (Hammer, 2007). The above indicates that maturity is the property of an object. It relates to a person or a

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subject and is a state that enables gradual continuous improvement (Gokalp et al., 2017; De Carolis et al., 2017). The maturation process is the ability of an organisation, including its processes, to systematically improve the results delivered as part of the conducted activity (Mielcarek, 2017). Process maturity is perceived as the scope in which processes are formally defined, managed, flexible, measured, and effective (Grajewski, 2007). In other terms, process maturity is indicated as a degree of optimal allocation of the organisation's resources in stable and measured processes (Grela, 2013).

Process maturity mainly concerns the degree and scope of implementation of management concept processes in the organisation through the use of methods and techniques specific to it (Röglinger et al., 2012). Process maturity of an organisation is expressed within the scope in which the processes are dealt with (Dahlin & Gunnar, 2020), which usually refers to defining the processes, managing them, measuring them, and constantly improving them. The concept of a "process-mature" organisation is usually referred to as an organisation whose processes can be considered mature from a qualitative point of view. For a process to be considered mature, it has to be efficient, predictable, and deliver high-quality results (Kalinowski, 2020).

The latest publications on maturity refer to its technological aspects (Klessova et al., 2022), digital transformation maturity (Rodríguez-Espíndola et al., 2022), project management maturity (Alghail et al., 2022, Jawad & Ledwith, 2022), Industry 4.0 maturity (Naeem & Garengo, 2022, Ramanathan & Samaranayake, 2022), network maturity (Kuchenmüller et al., 2022), supply chain risk management maturity (Dellana et al., 2022), Shopfloor Management (SFM) (Kandler et al., 2022), and lean maturity (Muiamba, 2022), which is in line with the latest high-technology and digitization-based business orientation. The approaches presented focus on the idea of maturity itself, confronting it with various aspects of a company's activities.

While academics focus on epistemological aspects of maturation, the utilitarian perspective is not commonly implemented, making the comparison of the maturity assessment of various companies difficult even within the same model due to differences in data collection, processing, and interpretation schemes. To exploit the utilitarian perspective and develop the approach to assessing maturity in a service enterprise, we designed a research procedure driven by the following research questions.

RQ1: What criteria should be used to assess the maturity of processes in a service enterprise to reflect the intangibility of services?

RQ2: How should maturity criteria in a service enterprise be assessed?

RQ3: How should the assessment of individual maturity criteria be integrated into the process maturity assessment?

The development of a model dedicated to the service sector is justified by the importance of this area. According to data recovered from Eurostat (https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20211021-1, access: 18.06.2022), in 2020, services were the largest economic activity in the EU measured in terms of gross value added (GVA) generated. Services represented 73% of the total GVA of the EU, followed by industry and construction (25%) and agriculture (2%). In all EU countries, services had the greatest weight in the economy, varying between 58% in Ireland and 87% in Luxembourg. According to Eurostat, industry and construction-related activities had significant weights in the economies of Ireland (41%), Czechia (34%), Slovenia (33%), and Poland and Slovakia (both with 31%). Furthermore, 72.9% of the EU's employed population in 2020 was employed in the service industry, while 22.5% was employed in industry and 4.5% in agriculture.

LITERATURE REVIEW

The key terms recognised for the needs of the paper include the process approach (as service enterprises are generally process orientated) and the maturity model. BPM (Business Process Management) is a philosophy of process thinking management that offers solutions to today's problems (Jeston & Nelis, 2014). In fact, BPM is a comprehensive system for managing and transforming organisational activities (Röglinger et al., 2012). An important point of focus in BPM is process management in such a way that customers receive products and services effectively and efficiently (Hermkens et al., 2022; Glykasa & Kokkinaki, 2018).

BPM is a valuable tool in the process of gradual change, increasing the chance for process improvement (Melão & Pidd, 2000; Tolsma & de Wit, 2009; Jeston & Nelis, 2014; Schmiedel et al., 2020). It uses existing processes as a starting point for improvement and allows for an in-depth understanding and assessment of the current state, covering all aspects related to business processes in all areas of the organisation (Schmiedel et al., 2020; Vom Brocke & Mendling, 2018; Van der Aalst et al., 2016; Jacobs et al., 2013; Rosenbaum et al., 2018). The rapid pace of digitization in the 21st century increases the demand for BPM, because it allows for a more detailed examination and understanding of the processes in their organization (Mendling et al., 2020). Implementing BPM not only requires a completely new way of working, but also involves looking at your organisation from a different perspective. (Binci et al., 2019; Jeston & Nelis, 2014), combining technical aspects with human-centric orientation in a new and synergetic way (Binci et al., 2019; de Pádua et al., 2014; Tolsma and de Wit, 2009; Kerpedzhiev et al., 2020). The approach is not free from limitations and constraints, yet they can be dealt with using the BPM Maturity Model (Schmiedel et al., 2020; Pereira et al., 2019).

The idea of a maturity model was first described by Nolan (1973) and Crosby (1979). Maturity models are defined as a set of different tools and practices that allow, on the one hand, the skills of a given organisation in terms of management to be assessed, but also enable the improvement of key factors leading to the achievement of the set goals (Looy, 2014; Pullen, 2007; Hermkens et al., 2022). Maturity models are an established way to support requirements such as assessing the current situation, identifying a desired situation, and obtaining a possible evolution path (Becker et al., 2009), as they perform both descriptive and prescriptive/comparative functions (Becker et al., 2009; Pöppelbuß & Röglinger, 2011). They are a powerful tool that organisations can use to achieve their strategic goals (Klisenko et al., 2022; Klisenko et al., 2022; Klötzer & Pflaum, 2017).

The best-known IT maturity model is the Capability Maturity Model (CMM). Originally proposed by Paulek, Curtis, Chris, and Weber (1993) to aid this software development process, particularly in government projects, CMM later evolved as a tool for overall business process improvement (Klisenko et al., 2022).

Maturity models have become a practically used tool to evaluate processes and organisations, and the multitude of applications proves the importance of their role in the area of management. Among the dominant areas in which maturity models are used, the following have been identified (Santos-Neto & Costa, 2019): software (e.g. Ehrensperger et al., 2021), process management (e.g. Hamrol & Grabowska, 2020), knowledge management, project management, sustainable development (e.g.: Golińska-Dawson et al., 2021; Stachowiak & Pawłyszyn, 2021; Vásquez et al., 2021;), logistics (e.g.: Werner-Lewandowska & Kosacka-Olejnik, 2019; Werner - Lewandowska & Golińska-Dawson, 2021; Facchini et al., 2020), risk management (e.g. Resende et al., 2022), supply chain (e.g. Soares et al., 2021), education (e.g. Cardos et al. 2022), public sector, construction (e.g. Alankarage et al., 2022), service management (e.g. Werner-Lewandowska, 2020), medical sector, human management, product lifecycle management, and resource management (e.g. Golińska-Dawson et al.,2021). The above areas prove the important place occupied by maturity models in management sciences.

Maturity models were adopted as methods of measuring the progress of an organization in striving for continuous improvement in various areas of management. The assessment performed in the maturity models is carried out using methods such as (Santos-Neto and Costa 2019, p. 736): six sigma, ATC algorithm, fuzzy logic (e.g., Caiado et al., 2021; Soares et al., 2021), diagnostic survey method (questionnaires), AHP, and Grey Decision Making (GDM) (for example: Golinska et al., 2015; Oleśków-Szłapka et al., 2019). Since the Hammer and Champy business revolution manifesto (1993), the management and improvement of business processes have been the basic tasks of organisational design (Becker & Kahn, 2010; Buhl et al., 2011; Gartner, 2010; Sidorova & Isik, 2010; vom Brocke et al., 2011;). Among the various approaches supporting business process management (BPM), attention is increasingly paid to maturity models (Bucher & Winter, 2010; Weber et al., 2008; Scott, 2007; Becker et al., 2010).

In terms of BPM, two types of maturity models can be distinguished: process maturity models and BPM maturity models (Rosemann & vom Brocke, 2010; Lee et al., 2007; Hammer, 2007; Weber et al., 2008). BPM maturity models allow organisations to gain an insight into their current BPM maturity level and highlight the possibility of further improving BPM implementation by comparing the current maturity level with higher maturity levels (Hermkens et al., 2022).

MATERIALS AND METHODS

The research methodology designed and implemented in the research is presented in Figure 1. To answer the research questions defined and presented in the Introduction section, we first designed a list of processes that are implemented in service enterprises (Stage 1). The definition was based on the literature review and included 3 groups of processes: basic, support, and specific industry. In the next stage (2), we define the list of decision criteria (DC) to assess the maturity level in a service enterprise in order to answer RQ1. Concerning the management functional areas, we identified potential assessment/description options. The general criterion applied was the identification of the function – whether it is recognised within a specified process or not. If the function is not recognised in the process analysed, its maturity is recognised at the lowest level possible.

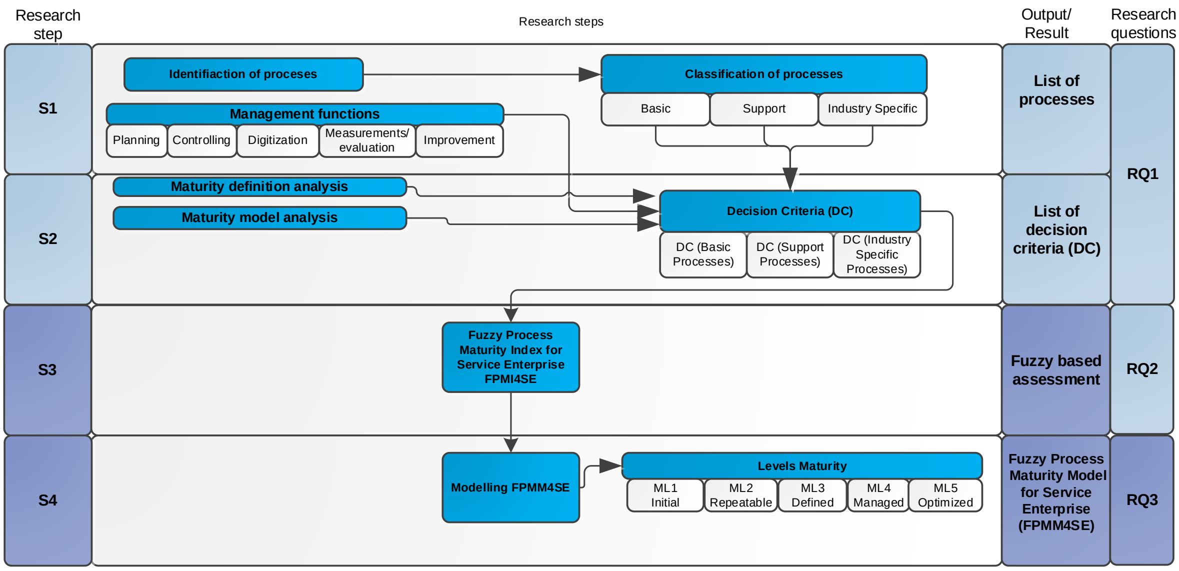

Fig. 1. The research methodology
Source: own work

If the function is recognised, its realisation mode is used as a detailed criterion. That is, the realisation of the function for the process analysed could be informal, ad hoc, systemized, and integrated. The criteria are organised in ascending order to show the path towards perfecting the function or the process. Example of Decision Criteria for Management Function (MF): the planning is presented in Table 1.

Table 1. Decision criteria (DC) - example

Decision criteria (DC)	Assessment
The process is not planned	Non-existent
The process is planned based on the experience of employees (no formalized methods)	Low level
The process is planned using own methods and tools	Medium-level
The process is planned using the best practices taken from the outside.	High-level

Source: own work

We used the list of decision criteria (DC) to develop the fuzzy process maturity index for service enterprise (FPMI4SE) in stage 3. It is based on linguistic variables and linguistic values used in processes assessment, and the calculation procedure had two steps: 1) calculating Fuzzy Process Maturity Index (FPMI) for every process and 2) calculating Fuzzy Process Maturity Index for Service Enterprise (FPMI4SE) as a fuzzy average of maturity assessment of individual processes. The calculated FPMI4SE is converted back into a linguistic value in the defuzzification process with the use of the Euclidean distance method.

The FPMI of predefined processes (Basic, Supportive, and Industry Specific) is calculated with formula 1.

$$FPMI_j = \frac{\sum_{i=1}^{n} MF_i}{5} \quad (1)$$

Where: *FPMIj* - Fuzzy Process Maturity Index of j-process, *j*- process index (j=1..5 for Basic processes, j=1..7 for Supporting processes and j=1..x for Industry Specific processes), *MFi* - level of individual management function i (non-existant, low, medium, high), and *I* - management function index.

After calculating FPMI for each process, it is possible to aggregate them into Basic Process Maturity Index, Supporting Process Maturity Index and Industry Specific Maturity Index, and holistic FPMI4SE.

In this stage, we strive to explain how to assess maturity criteria in a service enterprise (RQ2). Since the respondents gave their opinions in a descriptive way, we decided to translate them into fuzzy and use the fuzzy approach to calculate maturity level and understand the level of maturity of processes. For that purpose, triangular fuzzy numbers corresponding to low, medium, and high descriptors were implemented. To assess process maturity in the context of response to changes, we use the indicator based on the Fuzzy Agility Index (FAI) (Lin, 2003). As in the case of FAI and other examples indicated in the literature (Lin 2003; Lin et al., 2006), the use of elements of the theory of fuzzy sets in management is justified by the difficulties in formulating a precise assessment on a numerical scale. For process maturity assessment, we developed Fuzzy Process Maturity Index for Service Enterprise (FPMI4SE).

Stage 4 presents a conceptual approach on how to integrate the processed knowledge on the value of maturity assessment criteria (RQ3). As indicated in the theoretical background section, Business Process Maturity Models are useful from a company's perspective and strive toward continuous improvement. That is why we decided to use BPM approach and set the FPMM4SE (Fuzzy Process Maturity Model for Service Enterpricse) in the BPM Maturity Models framework, merging the approach presented in (Snabe et al., 2008) and the one by Gartner (O'Leary, 2009). The product of the merge is the model preselected in Figure 2.

Its structure comprises five levels, ordered incrementally. The levels are described in the context of planning, controlling, measurement and evaluation, improvement, and digitization.

To implement the model and assess the maturity of processes, descriptive characteristics of the levels should be used, addressed to functional areas of management identified in the previous stage. Consequently, if the processes are not planned, organised, controlled, measured, or improved, they are at an initial level of maturity, while if they are fully planned, organised, controlled, measured, and digitised, moreover continuously improved, they are at an optimising level of maturity.

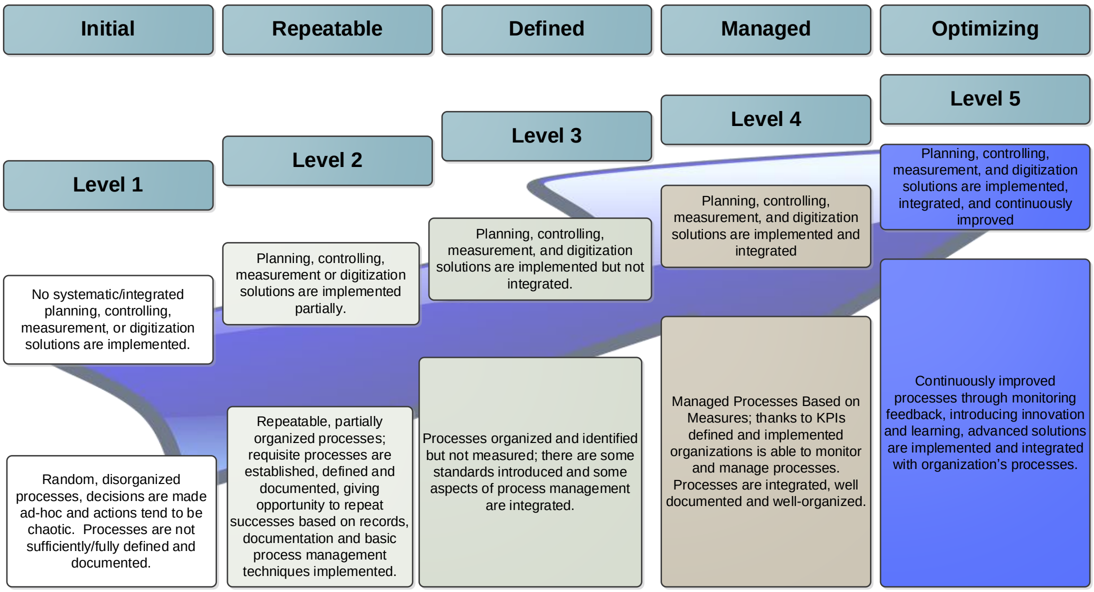

Fig.2.The Fuzzy Process Maturity Model for Service Enterprise – FPMM4SE
Source: own work

To identify the level of maturity, the Fuzzy Process Maturity Index for Service Enterprise (FPMMI4SE) was implemented. The procedure is presented in Figure 3, while the calculation scheme for fuzzy assessment is explained in the previous sections.

The procedure needs outputs in the form of business processes identified (BP - Basic Processes, SP, Support Processes, ISP, Industry Specific Processes) that are analysed in the context of management functions (MF) and assessed with the descriptive decision criteria by the experts. The assessment is translated into the fuzzy scale and after the assessment is completed, data is aggregated into FPMI4SE.

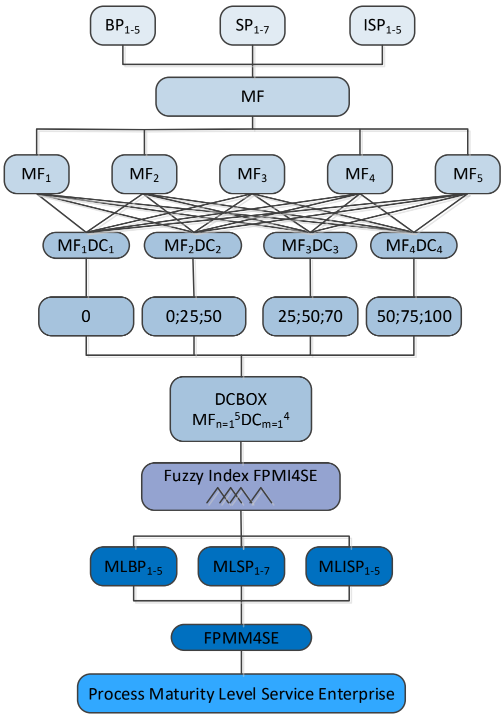

Fig.3. The procedure of Fuzzy Process Maturity Index for Service Enterprise - FPMMI4SE
Source: Own elaboration

The index is translated into the descriptive maturity level in the last stage of the procedure. As the index is based on FOMI, we used the same approach for defuzzification process. Hence, regarding the presented FPMI4SE measure, calculation of the Euclidean distance between a given fuzzy number and each of the fuzzy numbers representing the range of natural language expressions is implemented, as it is the most intuitive, and the others are difficult to implement (Lin, 2003). The following formula is used to calculate the Euclidean distance (formula 2).

$$d(FPMI4SE, JN_i) = \sqrt{(\sum_{x=1}^{p} f_{FPMI4SE}(x) - f_{Ni}(x))^2} \quad (2)$$

Where, *Ni*, natural language expression (assessment of the feature), *x* - point at which distance is measured, i, number of the point, p, number of points, FPMI4SE(x) - value at point x, for which natural expression is identified. fNi(x) - the distance in every x point.

The linguistic value closest to the determined index corresponds to the level of the assessed process. The assessments of individual features are used to determine the aggregated maturity level. Thus, aggregated maturity level calculation requires the determination of evaluation for maturity features and then calculation, based on the identification of a number of average or higher-rated features, drawing conclusions about the overall (aggregated) assessment. Simple decision rules (IF..THEN…) are used to aggregate the assessment (Table 2).

Table 2. Decision rules for aggregating the assessment

	Number of MF	Assessment		Maturity Level
IF	0	assessed at a medium level or higher	**THEN**	Initial (ML1)
	most 2			Repeatable (ML2)
	3	assessed at a medium level or higher		Defined (ML3)
	4 or more	assessed at a medium or higher level		Managed (ML4)
	3 or more	evaluated at a high level;		Optimised (ML5)

Source: own work

The presented procedure is based on the assumption that all processes are equivalent and that the level of maturity is evidenced by their joint and synergistic occurrence at least at a medium level.

RESULTS

The research was carried out in a real business environment to validate the procedure designed and benefit from the feedback from the organisation evaluated. Research was carried out in the period from December 2021 to February 2022 and followed the stages presented in the previous section.

The research procedure was implemented to assess process maturity in a selected company representing the service industry. Following the research procedure, we needed to identify processes realised in the enterprise. We used the basic and supporting processes list and after consulting experts representing the enterprise completed it with a list of Industry Specific Processes. Experts evaluated the processes according to the adopted decision criteria (DC). 21 experts — process managers (process owners) — participated in the study. The analysis of the responses allows us to assess process management and identify process maturity. Each process was evaluated with the implementation methodology. Data were collected with respect to research ethics and privacy, and contribution was voluntary. The inputs and outputs obtained in the research are presented and characterised in Table 4.

Table 4. The inputs and outputs

Linguistics Variable	Type	Range	Value	Triangular fuzzy number
MF1-MF5 v (management functions)	Input	0-100	Non-existant	-
			Low	(0, 25, 50)
			Medium	(25, 50, 75)
			High	(50, 75, 100)
ML1-ML5 (maturity level)	Output	0-100	Initial (ML1)	(0, 0, 25)
			Repeatable (ML2)	(0, 25, 50)
			Definition (ML3)	(25, 50, 75)
			Managed (ML4)	(50, 75, 100)
			Optimised (ML5)	(75, 100, 100)

Source: own work

On the basis of the defuzzification process described in the previous sections, linguistic expressions referring to maturity were identified. The calculation results indicate that the process maturity of basic and industry-specific processes is one level higher than the process maturity of support processes. The assessment is quite homogeneous, as only Level 2 and Level 3 are identified. In the assessment of management functions, however, the spectrum is wider, as low, medium, and high assessments are identified. The functions assessed at the low level are the ones requiring improvement. They are executed using an ad hoc approach without procedures or best practices, and no systemic tools are designed and used for them. The functions executed at the medium level can be improved, yet some effort has already been made to organise and systemise them. The functions executed at the high level are systemized and continuously improved, which means they can be a benchmark in the company. The management functions executed at the highest level in the company assessed were planning and controlling, which seems to be a good starting point for increasing maturity: high-quality planning initiates high-quality performance. Concerning the processes, the ones best assessed are basic ones and industry specific. The results of the calculation are compared with the decision rules presented in the previous sections. The procedure is based on the assumption that all processes are equivalent, and the level of maturity is evidenced by their joint and synergistic occurrence at least at a medium level.

There are differences in maturity assessment with the calculation procedure (results of assessment of management functions are aggregated as fuzzy average) and conditional assessment (results of assessment of management functions are used in IF..THAN conditions designed). There is greater variety in results obtained in conditions-based procedure (the levels vary from initial to managed, while in calculation procedure there is only repeatable and defined level). The possible reasons for the difference can be the following. The IF..THAN procedure is not precisely designed, the calculation procedure gives the result in the form of the average, eliminating higher and lower results.

Taking into account the above, the use of both approaches seems to be justified. The conditions-based procedure is more sensitive and identifies slight deviations from the maturity levels in the maturity model, which can be useful when analysing processes in detail, while the calculations-based average identifies the overall process maturity.

CONCLUSIONS

This paper proposes a novel service enterprise process maturity assessment model, FPMM4SE, based on a fuzzy probabilistic expert system (FPMI4SE) that overcomes the inaccuracy and uncertainty often found in process maturity models. This article fills the research gap by providing a theoretically grounded and methodologically rigorous Process Maturity Model (PMM) for a service enterprise. By referring to the research questions posed in the introduction, the article fills the gap in the epistemological and utilitarian aspect.

First, it indicates how to select the scope of the maturity assessment (RQ1): highlighting the issues of main, auxiliary, and industry-specific processes, which is in line with the process approach, focused on processes that add value to the customer. In companies providing services, due to the intangible nature of the product offered on the market, basic processes are often not diagnosed or incorrectly defined, which is why they are improperly managed.

Secondly, the proposed model FPMM4SE gives clear and measurable evaluation criteria (RQ2), which is legible for the assessor, thus eliminating ambiguity and subjectivity.

The FMMI4SE developed by us enables the processing of knowledge concerning the value of the maturity assessment criteria (RQ3). The original model of process maturity integrates the processed knowledge concerning the value of the maturity assessment criteria. It allows the assessor to clearly state at which of the five possible maturity levels (ML) the processes implemented in the enterprise are.

From an industrial perspective, this article presents a robust diagnostic tool to help service companies manage their process by enabling them to discover the true level of process maturity in FPMM4SE.

As for directions for further research on the process maturity of service enterprises, we indicate the improvement of the proposed model, its validation in other service sections, and its adaptation to other areas of enterprise activity, such as logistic, digital, and sustainable maturity.

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ORIGINAL PAPER

THE EFFECTS OF SUPPLY CHAIN COMPLEXITY ON RESILIENCE – A SIMULATION-BASED STUDY

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ABSTRACT. Background: The aim of the paper is to analyse the effects of disruptions on supply chain performance and overall resilience. In recent years, global supply chains have been under great pressure and faced many challenges, like demand fluctuation, lack of raw materials or supply, disruption of transportation corridors and lockdowns. As a response to this, global companies started to reorganize their supply chains, trying to save and maintain their core operations by reshoring, multiple sourcing or increasing their inventory levels, and thereby reaching a higher level of long-term supply-chain sustainability.

Methods: The disruptive changes in transportation resources and their overall impact on supply chains and their complexity were explored. By using the simulation tool Simul8, hypotheses on how disruptive events influence supply chain performance were tested. The model tested key performance indicators (KPIs) of 3- and 4-tier supply chains, primarily average lead time in the system, average idle time in process, and resource utilization level.

Results: In this study, a standard 3-tier supply chain model was compared with a 4-tier supply chain model to determine how KPIs change when there is disruption to transport and storage capabilities. The results indicate that in case of disruption, the 3-tier supply chain performs better than the 4-tier supply chain, even if the 4th tier is a cross-docking center inserted into the system to be able to react to demand fluctuations quickly. Based on this outcome, complexity does not serve resilience.

Conclusions: Based on the simulations performed, recommendations are formulated for practitioners on how to develop the structure of supply chains, taking into account their level of resilience.

Keywords: supply chain structure, resilience, simulation, Simul8

INTRODUCTION

In practitioner papers and supply chain portals, companies report on various methods they have used to try to handle the disruptive events of recent years. There are only a limited number of studies and academic papers pointing out how supply chain complexity reduction or inventories can help increase resilience. At the same time, there is only a limited amount of research involving large samples, statistical analysis or simulation. For this reason, the developed simulation models of 3-tier and 4-tier supply chains, based on real geographical data, represent a contribution to a better understanding of potential and real ties and their behaviour when some disruptive constraint appears.

The aim of this paper is to contribute to the assessment of disruptions on supply chain performance and overall resilience. In recent years, global supply chains have come under significant strain, grappling with various challenges, such as demand fluctuations, shortages of raw materials or supplies, disruptions in transportation routes, and lockdowns [Guann et al. 2020]. As a response, global companies started to reorganize their supply chains, trying to save and maintain their core operations by reshoring, multiple sourcing or increasing inventory levels [Medyakova et al. 2020] to increase the long-term sustainability of their supply chains [Nagy et al. 2022].

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In this study research results are presented about how the complexity of a supply chain affects its resilience to a specific disruption [Helou and Caddy 2006; Rangel et al. 2015]. A standard single 3-tier supply chain model was developed, and its complexity was enhanced by additional tiers. Since the role of transportation in effective customer satisfaction is widely discussed [Jałowiec and Dębicka 2017], the main focus of the study was disruptions threatening the transportation process. By using the simulation tool Simul8, the influence of disruptive events on supply chain performance was tested [Rehak et al. 2023; Nagy and Foltin 2022]. The authors hypothesise that the level of complexity and the number of stock-keeping points in the supply chain increase the level of resilience. Simul8 and a standard sample dataset were used to test supply chain structures with different complexity and inventory levels.

The paper is structured as follows. In the literature review, supply chain resilience is defined, and measures are described. The methodological applications of the modelling and simulation help in understanding complex supply chains and their disruptions. In the modelling and simulation, a What-If analysis is applied to identify possible connections within the complex systems and possible sources of increased resilience. In the results section, the findings are presented. In the discussion and conclusion the main message of the research is summarized, together with the limitations and future research directions.

SUPPLY CHAIN RESILIENCE AND THE ROLE OF SIMULATION

Supply chain security refers to the measures that are taken to protect the integrity and reliability of a supply chain. This includes protecting against physical threats such as theft, tampering, and natural disasters, as well as cyber threats such as data breaches and cyberattacks [Dey et al. 2022; Tonn et al. 2019]. Supply chain resilience, on the other hand, refers to the ability of the supply chain to withstand disruptions and continue to function effectively [Ponomarov and Holcomb, 2009]. This includes the ability to adapt to changing conditions, recover from disruptions and maintain the delivery of goods and services to customers, together with minimization of the impact of disruptions and the maintenance of operational efficiency [Jámbor and Nagy 2022; Stone et al. 2020; Yao and Meurier 2012].

One of the most critical processes in supply chains is transportation. During recent years, there have been many disruptions in the transportation networks of global supply chains, e.g. border and port lockdowns during the Covid-19 pandemic or the Suez Canal incident. Within transportation networks, vulnerability refers to susceptibility to external disruptions that could diminish service performance. In contrast to the concepts of network robustness and reliability, vulnerability analysis places greater emphasis on understanding how external interference can affect a network [Sun et al. 2022]. Traffic congestion, as per the definition provided by Weisbrod et al. [2003], arises from traffic delays resulting from the volume of vehicles on the road surpassing the transportation network's capacity. This phenomenon is a common occurrence in everyday life, particularly during peak rush hour periods, but can be extreme in case of a natural disaster [Chang et al. 2022; Cárdenas et al. 2018].

There are several ways to increase the resilience of a supply chain [Rennane et al, 2022]. One method is to assess the vulnerabilities and risks within the supply chain, and then implement measures to mitigate or eliminate those risks. This can include measures such as diversifying the supply chain, building redundancy into the system, and implementing robust contingency plans. The performance of transportation networks is vulnerable to variations stemming from a combination of factors, including traffic incidents, construction zones, weather conditions, special events, control mechanisms, and shifts in demand [Filipovska et al. 2021].

Another method is to conduct regular simulations or exercises to test the resilience of the supply chain. These can include simulations of various types of disruptions, such as natural disasters, cyberattacks or supply chain breakdowns, to see how the supply chain responds and to identify any weaknesses that need to be addressed.

Simulation is a method that can be used to realistically model the operation of processes and systems so that their state changes can be evaluated [Tamás, 2017]. There are several advantages of simulation modelling: it is cheaper and safer than testing the real system and the model can be tested in parallel with the real system [Gubán, 2017]. Simulation software analyses the complex system by mimicking its real behaviour, but because it only considers the important elements, it is much simpler than the real model [Gubán, 2017]. So, the model is actually a simplified version of the real system that works in reality. It is an attempt to describe how the system works so that it can be analysed. These models are created with a specific objective in mind, such as reducing operational risks or costs, but also to increase customer satisfaction.

Byritis [2014] used Simul8 in his dissertation to simulate the time needed to cross the port of Dover, and the dimensions he evaluated were time and performance. By modelling port transit processes, the simulation helped him find the bottlenecks. Filipovska et al. [2021] dealt with the problem of travel times in a transportation network and found Monte Carlo Simulation (MCS) an appropriate tool for the estimation of path travel time distributions. Suryawanshi et al. [2021] used MCS in sensitivity analysis when analysing the impact of operational risk, demand uncertainty and perishability on the expected costs in e-commerce supply chains. Sopha et al. [2020] applied Agent-based Modelling methodology and Netlogo software to simulate the long-term performance of regional distribution centres in archipelagic logistics systems in Indonesia. They found that a hub and spoke distribution system can be more cost effective. Wang et al. [2022] used the SUMO simulation package to design the optimal routing strategy for shuttle buses at Dallas Airport (DFW). Chang et al. [2022] used a simulation optimization technique, sample average approximation methodology, to solve the split delivery multiple destination inventory routing problem in the case of an earthquake in Thailand, and they were able to obtain the best vehicle and inventory routing decision under varying disaster scenarios. As can be seen, researchers have used various simulation methodologies and software packages to study a variety of problems while analysing the transport process, but no research could be identified that examines the impact of supply chain complexity on resilience in case of a disruption in transport.

Based on this literature review, the following hypothesis was formulated:

H1: A supply chain with higher complexity has greater resilience towards disruptive events that limit the availability of transportation capabilities.

In the next section, the plan for the simulation is introduced, and the exact methodology is described in detail.

THE SIMULATION MODEL

Simulation plan

The study analyses how supply chains with different structures react to disruptive events in the transportation process given the same initial supply, inventory and demand data.

The disruptive events in the model affect transportation capabilities. The network's configuration, the existence of travel patterns, and the interdependence of traffic flow between its segments further introduce spatio-temporal interconnections among travel times within the network [Filipovska et al. 2021]. The assessment of travel times is of paramount importance when examining the operational effectiveness of the network [Stajniak and Koliński, 2016].

The inserted distribution centres and cross-docking facilities serve as hubs responsible for aggregating and merging the complete supply of goods, subsequently dispersing these items to various national regions. Optimization and simulation represent the predominant modelling methodologies applied extensively in the realm of supply chains, especially concerning the identification of the most advantageous node placements within a network [Sopha et al. 2020].

A significant challenge in simulating transportation systems lies in the validation of simulation models as accurately mirroring real-world conditions. This challenge arises from the stochastic characteristics of both the micro-level behaviour of drivers and the macro-level properties of road links, necessitating a close correspondence between the statistical outcomes of a substantial volume of simulations and real-world observations [Wang et al. 2022].

The scenarios are theoretical and were tested in Simul8 software. The applied supply chain models are based on the supply chain structures operated by a fictional global company. The sample company is a large company, having subsidiaries throughout Europe and the world. The supply chains it operates represent different levels of complexity both in terms of horizontal and vertical structure as well as in global-local extension; however, we focused on European final product distribution. It was supposed that each supply chain handled the same standard product based on a pallet unit, and the simulations used the same initial supply and demand data. Similar disruption occurred through reduction of the transportation capacity available as a result of a disruptive process. For this reason, four scenarios were tested:

- Model #1: 3-tier supply chain model operating under standard conditions;
- Model #2: 3-tier supply chain model with disruption;
- Model #3: 4-tier supply chain operating under standard conditions;
- Model #4: 4-tier supply chain with disruption.

The results would thus allow the hypothesis to be verified or rejected and answer questions regarding the relevance of supply chain complexity and inventory level in the context of disruptive events.

Design of simulation

The overall research is based on theoretical modelling of the realistic variants of supply chains in the simulation environment Simul8. The initial modelling assumptions are the following:

- the distribution scenarios start from the port of Trieste (Italy) and pass through a cross-docking centre in Maribor (Slovenia) to cover customer needs in and around Budapest (Hungary) and Brno (Czechia);
- distribution models cover distribution from the port of Trieste through the port storage facility, the distribution of palletised unit loads on trucks to a cross-docking centre in Maribor, which is an important crossroads on the highways to the targeted regional distributional areas, which are the surroundings of Budapest and Brno;
- for further testing of supply chain resilience, based on the availability of drivers/trucks, road availability and storage constraints (time and capacity), both 3-tier and 4-tier models were tested, with further consideration of an additional cross-docking in Bratislava (Slovakia);
- on the basis of the developed model, a suitable simulation timeframe was identified by the What-If testing method, where the distribution of the considered material within the selected time constraints given by the working hours did not exceed 6 working days, i.e. the timeframe for the simulations was chosen to be 6 working days, from 9 a.m. to 4 p.m.;
- the distribution roads are highlighted in Figure 1.

The overall approach in the modelling application was implemented in steps: (1) creation of the basic model structure, (2) initial model setup, (3) setting of ideal conditions and overall model optimization, (4) What-If analysis to test the resilience of the prepared models at three levels of efficiency of the resources used (trucks and drivers) and the supply chain elements (cross-docking centres and regional depot).

Fig. 1. Regional dimension of the developed models. Source: own work.

Two optimized models were tested, and both were examined in the context of possible disruptions to transportation resources and capabilities. The developed models were:

- Model #1: 3-tier supply chain model operating under standard optimised conditions, with the structure depicted in Figure 2. This model represents the case of a supply chain originating at the Port of Trieste, continuing through port storage and distribution capabilities to a cross-docking centre located in Maribor, and then splitting into two directions to regional centres in the Budapest and Brno regions, with three local depots each.
- Model #2: 3-tier supply chain model with disruption, with the same structure as Model #1, as depicted in Figure 2;

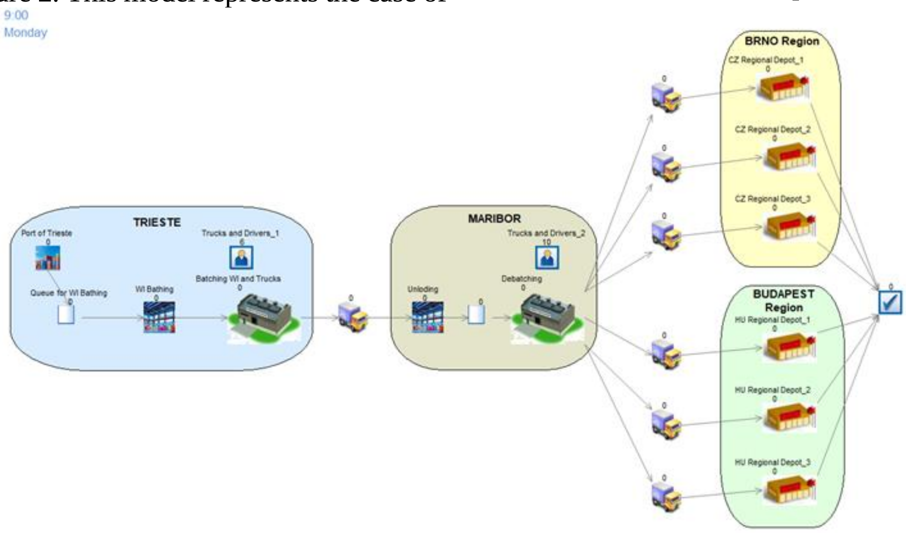

Fig. 2. The 3-tier supply chain model. Source: own work.

- Model #3: 4-tier supply chain, operating under standard optimised conditions, with the structure depicted in Figure 3. This 4-tier supply chain contains an additional regional cross-docking centre located in Bratislava, with the main purpose of satisfying uncovered demand in Budapest and Brno regional depots.
- Model #4: 4-tier supply chain with disruption, with the same structure as Model #3, as depicted in Figure 3.

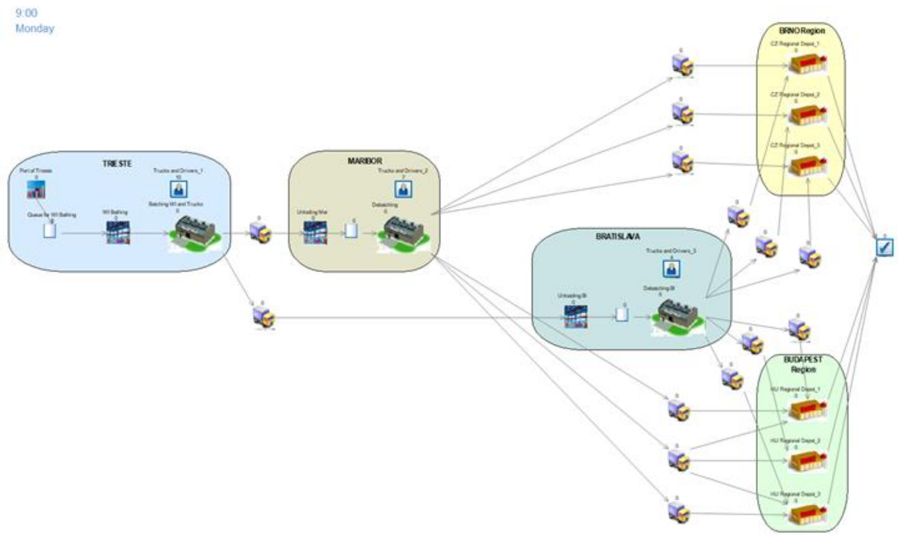

Fig. 3. The 4-tier supply chain model. Source: own work.

Models #2 and #4 were tested according to the key features of real conditions [Kolinski et al, 2017]. Key performance indicators (KPIs) of the two supply chains were tested, primarily lead times and the rate of utilisation of transport capacities while minimising overall distribution times [Sun et al. 2022; Sliwczynski & Kolinski, 2016; Dujak et al, 2017]. At the same time, changes in the overall efficiency of transport and storage capacity utilization, the percentage of drivers working and waiting times were examined.

Model assumptions and limitations

Certain assumptions and constraints had to be made to develop the models and their subsequent testing. However, individual constraints were chosen to ensure that the basic criteria and model functionality were consistent with reality. The model parameters were as follows:

- 1000 pallet units were distributed from the port facility to the port storage facility every 2 minutes;
- trucks/drivers only left the port storage facility fully loaded (FTL), and the maximum capacity of a vehicle was 20 pallets;
- the average speed of the trucks was 80 km/h, with working hours for drivers from 9 till 16 hrs every working day, from Monday to Friday;
- a rounded uniform distribution with a lower bound of 10 and an upper bound of 20 was adopted, meaning that trucks left the cross-docking centre with at least 10 pallets, up to a maximum capacity of 20 pallets;
- all storage capabilities were unified;
- distances and speed within both models were as follows:
  - Trieste-Maribor was 240 km, with 180 mins as a minimum time for a truck to cover the distance;
  - Maribor-Budapest was 350 km, rounded to 260 mins as a minimum time for a truck to cover the distance;
  - Maribor-Brno was 390 km, rounded to 290 mins as a minimum time for a truck to cover the distance;
  - Trieste-Bratislava was 550 km, rounded to 410 mins as a minimum time for a truck to cover the distance;
  - Bratislava-Budapest was 200 km, rounded to 150 mins as a minimum time for a truck to cover this distance, and 100 mins as a minimum time to cover the distance of 130 km between Bratislava and Brno;
  - the average time for drivers and trucks to return to their original destinations was 180 mins for Maribor-Trieste, 290 mins for Budapest-Maribor and Brno-Maribor, 410 mins for Trieste-Bratislava and 150 mins for Bratislava-Budapest/Brno;

- the optimised models were set up for ideal conditions, without any significant sources of disruption exceeding standard normal distribution values.

SIMULATION RESULTS

The actual construction of Models #1 and #3 was intended to reveal the relationships within 3-tier and 4-tier supply chains. Within the basic setup of Models #1 and #3, the models created were primarily optimised for the most efficient use of resources, i.e. the available capacity of trucks and drivers.

Results of Optimal Model Conditions

The optimised #1 3-tier supply chain model was tested by applying a possible disruption in the available resources in transportation and the availability of cross-docking centres and depots. The disruption affected all 3 tiers of supply chain model #1. Then 3 scenarios were tested representing different extents of disruption, as Preston et al. recommend [2018]: thanks to the indicated disruption only 99%, 95% and 90% of the functionality of the optimal model was available. Similarly, the Model #3 4-tier supply chain with disruption was tested, having 99%, 95% and 90% of functionality and capabilities available.

Table 1. The results from the developed models and their tests

Model	resource utilisation [% level of availability]		average time in system [min]	average waiting time in process [min]
(1) 3-tier chain	#1 trucks/drivers: #2 trucks/drivers:	66.3% 61.4%	545.17	11.56
(2) 3-tier chain under disruption	#1 trucks/drivers [99%]: #2 trucks/drivers [99%]:	32.0% 34.1%	546.07	12.94
	#1 trucks/drivers [95%]: #2 trucks/drivers [95%]:	36.5% 38.7%	548.98	12.38
	#1 trucks/drivers [90%]: #2 trucks/drivers [90%]:	40.7% 42.6%	561.41	15.59
(3) 4-tier chain	#1 trucks/drivers: #2 trucks/drivers: #3 trucks/drivers:	34.4% 35.0% 56.6%	604.22	13.39
(4) 4-tier chain under disruption	#1 trucks/drivers [99%]: #2 trucks/drivers [99%]: #3 trucks/drivers [99%]:	35.3% 36.0% 57.7%	604.16	13.27
	#1 trucks/drivers [95%]: #2 trucks/drivers [95%]: #3 trucks/drivers [95%]:	39.5% 39.3% 61.6%	612.85	15.39
	#1 trucks/drivers [90%]: #2 trucks/drivers [90%]: #3 trucks/drivers [90%]:	43.2% 45.0% 67.0%	641.02	25.80

Source: own work.

The simulations showed that strengthening the 3-tier supply chain structure with an additional cross-docking centre does not have clear benefits for the resilience of the chain as a whole. The interconnection of the individual parts of chains was considered. For example, in the 3-tier model, when we used 6 trucks/drivers between tiers 1 and 2 and 10 trucks/drivers in tier 3, the efficiency of the trucks/drivers between tiers 1 and 2 was 61.4% and the efficiency of the tier 3 trucks/drivers was 66.3%. Increasing the number of tier 3 trucks/drivers from 10 to 11 caused a decrease in the efficiency of the tier 1 and 2 truck/drivers (from 61.4% to 55.8%), while the efficiency of the tier 3 trucks/drivers remained the same, 66.3%.

The reduction in the availability of resources (trucks/drivers) and the efficiency of cross-docks and depots in the 3-tier supply chains resulted in a difference between the optimal variant and the capability constraint (90% availability) – an average difference of 16.24 mins. In the case of the 4-tier supply chain, despite the additional cross-docking centre and the increase in transportation capacity (trucks/drivers resources), the difference in average times between the optimal and the 90%-capacity variants was 36.8 mins. In absolute terms, for the 3-tier and 4-tier supply chains, this is a difference of 545.17 mins compared to 641.02 mins, which is 14.2% more time to cover the average distances in the model.

The same is true of the average waiting times in the system, since the difference in the average waiting time between the optimal case and the case of limited availability of resources in 3-tier supply chains is relatively small. In the case of a decrease in the performance of the entire chain by 1% or 5%, the difference in the delays when passing through the system is negligible (less than 1 min). When only 95% of capacity is available in the 3-tier chain, the reduction of waiting times – compared to the 99% variant – becomes interesting. This fact points to a certain paradox, since despite the temporary lack of availability of resources and a higher rate of waiting in the system, the overall efficiency can be even higher.

In the case of 90% availability of supply chain capacity, the increase in waiting time to pass through the system was 4.03 mins, which is a 34.9% increase. In the case of 4-tier supply chains, a 1% drop in performance results in a slight reduction in the average waiting time. On the contrary, a higher level of disruption in the 4-tier supply chain causes an increase in delays of 14.9% when the capacity is limited to 95%. When the capacity of the chain is significantly disrupted and only 90% of capacity is available the increase in delays is 92.7%.

Utilization of cross-docking capabilities during the whole simulation

The application of the concept of cross-docking centres aims to handle and balance fluctuating demand and optimize distribution channels. If capacities are sized appropriately, they allow the absorption of possible disruptions in the flow of materials, both up- and down-stream. This was also the case in the 3-tier and 4-tier models, where the object of the investigation was to identify the absorption capacity of each type of supply chain. The effort was focused on determining, for the chosen case study, which of the supply chain types exhibits a greater ability to absorb potential disruptions.

In the proposed 3-tier and 4-tier supply chains, the cross-docking centre in Maribor plays a decisive role. For a 3-tier supply chain, in optimal conditions, 25.62% of the warehouse operations are picking/stocking and the remaining average time required for the distribution of all pallets (545.17 min. in ideal conditions) represents 74.37% of the time, when the warehouse performs the role of storage and is waiting for the next order or dispensing material. In this case, there are no other conditions such as waiting due to unavailability of resources, system overload, or system blockage (Figure 4).

In the case of a 10% limitation of distribution and resource capacity, the average distribution time increases to 561.41 mins, and warehouse utilization during loading/unloading operations increases to 30.75%. The potential expected increase in cross-docking centre capacity utilization is reduced by 6.56% due to the need to wait for available transportation resources (i.e., trucks/drivers) and by 7.17% due to overcrowding of the centre hindering it in performing its function. The changes in centre efficiency are shown in Figure 4, on the left for optimal conditions and on the right for the situation where capacity is constrained to 90% of the optimal conditions. If the total capacity of the cross-docking centre drops to 90%, the available capacity drops to 13.73%.

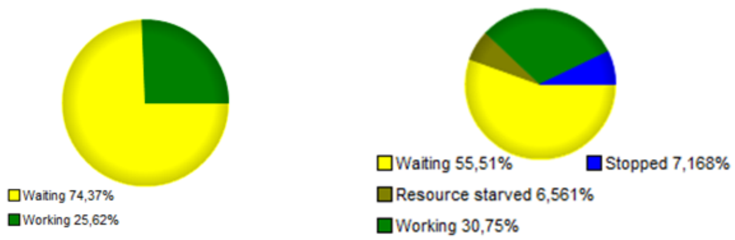

Fig. 4. Utilization of cross-docking centre in Maribor, under optimal conditions (left) and under 90% system efficiency (right). Utilization of cross-docking centre in Maribor in the 3-tier supply chain, under optimal conditions (left) and under 90% system efficiency (right). Source: own work.

The 4-tier supply chain already exhibits longer average transit times in the optimized state, given the same distances and distribution conditions (Figure 5). Under optimal conditions, the 4-tier supply chain time requirement in the cross-docking centre in Maribor for loading/unloading operations is 12.18%, and in the cross-docking centre in Bratislava represents 8.44% of the total time. In the case of capacity constraints due to disruption in functionality resulting in only 90% available capacity in the 4-tier supply chain, the utilization of the cross-docking centre in Maribor remains at the same level; however, resource needs increase to 5.94% and the time requirement increases from 8.44% to 9.91%.

In case of the Bratislava cross-docking centre, the active use of resources also remains at the same level, but their availability is limited; distribution takes place only 6.54% of the time, and the warehouse is unavailable for 10.61% of the simulated time. A combined representation of the simulated availability of cross-docking centre capacity in Maribor and Bratislava within a 4-tier supply chain is shown in Figure 6.

The simulated real usage of the Maribor centre drops by a total of 15.85% when the system capacity availability drops by 10%. In the case of the cross-docking centre in Bratislava, when the system availability drops by 10%, its efficiency drops by 17.15%. Moreover, the reduction in capacity availability is 34.9%, which is more than in the 3-tier supply chain.

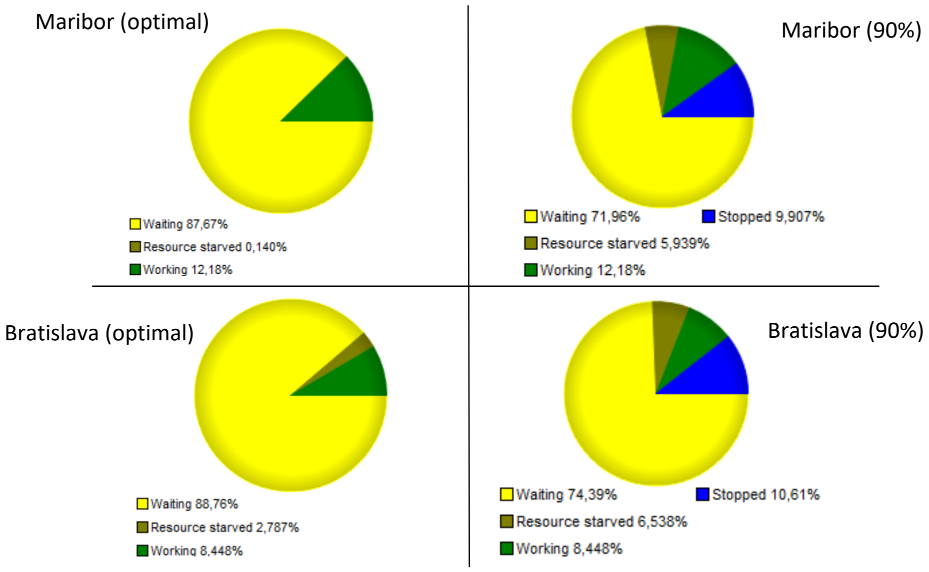

Fig. 5. Utilization of the cross-docking centres in the 4-tier supply chain, under optimal conditions (Maribor left top, Bratislava left bottom) and under 90% system efficiency (Maribor right top, Bratislava right bottom). Source: own work.

A limitation of the simulations and the results is that the efficiency of cross-docking centres in the whole simulation was calculated assuming that they worked for six working days between 9 am and 4 pm. The time distribution in Figure 4 and 5 are based on these working hours.

To better understand the impact of potential supply chain disruptions and capacity constraints, it is useful to observe the utilization patterns throughout the simulation study. A time analysis of the availability and capacity utilization of the cross-docking centre in Maribor for 3-tier and 4-tier supply chains is shown in Figure 6.

The time courses (Figure 6) show a difference in absorption capacity between the 3 and 4-tier chains. Within the 3-tier chain, there is less frequent congestion of individual system elements (upper part of the image, blue colour), unlike in the 4-tier supply chain (lower part of the image, blue colour). Also, within the 4-tier supply chain, more frequent blocking of entries to cross-docking centres can be observed (lower part of the image, red colour). In the same way, there is a more significant reduction in the suspension of distribution processes due to the limitation of transport and distribution capacities, such as trucks and drivers (lower part of the image, dark-green colour).

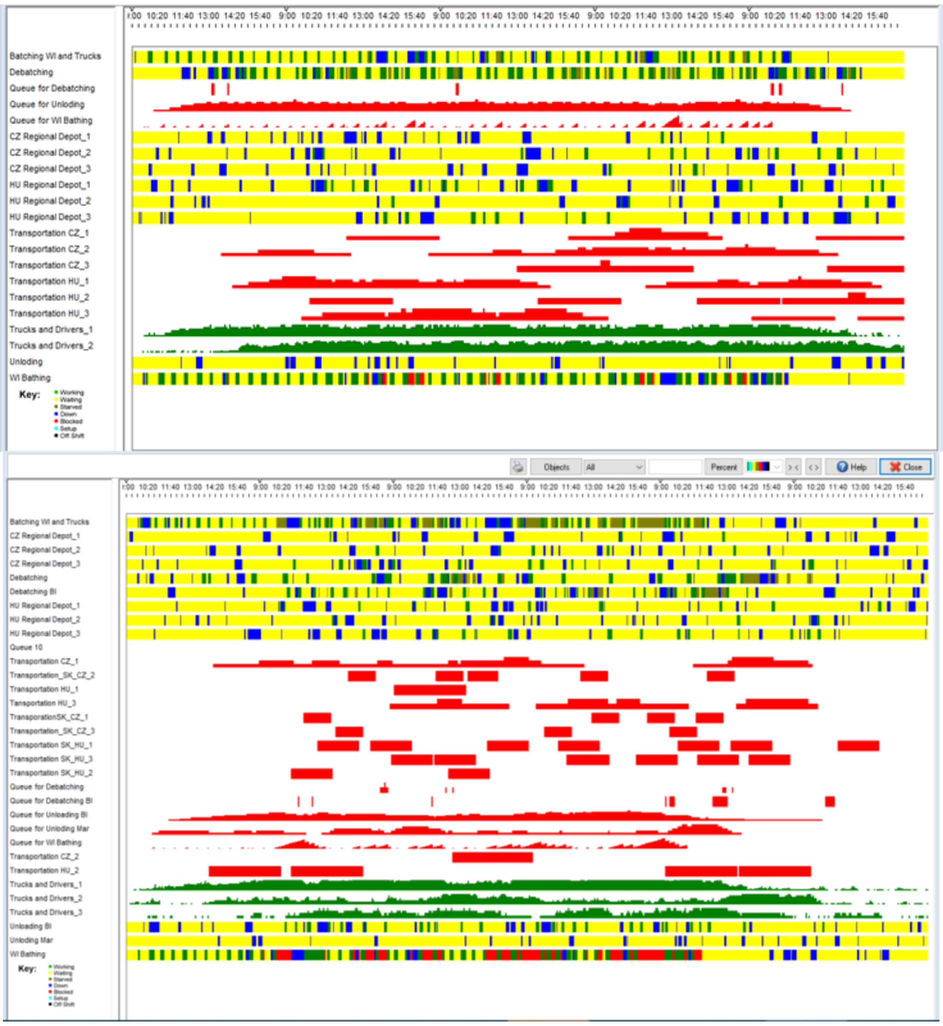

Fig. 6. Comparison of the time course of 3-tier (top) and 4-tier (bottom) supply chain model functionality when capacity and resource availability drop to 90%. Source: own work.

DISCUSSION AND CONCLUSION

The aim of the conducted research was to contribute to a better understanding of the relationships and ties within supply chains and their ability to face possible disruptions. Although a number of studies have used simulations to investigate elements of the transport process, even at the supply chain level, no studies were found that correlated the complexity of a supply chain with its resilience to a disruptive event. In this respect, this study is unique, and its findings do not confirm preliminary expectations.

In the simulation, Preston's [2018] approach was applied, and pessimistic, normal and optimistic scenarios were tested for disruption in the transport process. The problem was approached from the micro point of view [Wang et al. 2022], and the operative transport capabilities were analysed. The travel time (transit time) of goods proved to be crucial in the current model [Filipovska et al. 2021] and was sensitive to exogenous operational conditions. The study confirmed the statements of Sopha et al. [2021] about point-to-point networks having lower performance than a hub-and-spoke system, and this is a good further improvement possibility for the research. Suryawanshi et al.

[2021] proposed prepositioning inventory, and Yang et al. [2021] argue for surplus inventory as disruption management techniques. The study does not support these ideas, as additional stock-keeping points in the 4-tier supply chain did not increase resilience.

Within the identified research gap, models of 3-tier and 4-tier supply chains were created and their ability and effectiveness to absorb potential disruptions of supply chains and efficiency were tested. The created models were optimized through a What-If analysis and set to a stable level showing optimal use of resources (primarily trucks/drivers). Subsequently, disruption of their functionality was investigated at 99%, 95% and 90% of the original optimized level. In order to realize the examined links of 3-tier and 4-tier supply chains, a theoretical geographically localized model was chosen to analyse the possibilities of distributing 1000 pallets from the port of Trieste through an imaginary cross-docking centre in Maribor, with subsequent distribution to the regions around Budapest and Brno. For the 4-tier supply chain, a compensating cross-docking centre was added to the 3 tiers to better absorb potential disruptions.

From the experiments carried out for the given region, the given distances and the throughput of the road network, it was found that:

- the 3-tier supply chain had a higher time efficiency in an optimized state without disruption, on average by 9.8% compared to the 4-tier supply chain, while at the same transportation resource requirements were 31.3% lower compared to the 4-tier supply chain;
- when the available capacities and resources were limited to 90% of the optimized state, the 3-tier supply chain was 14.2% more time-efficient than the 4-tier supply chain, with the same resource needs as in the optimized state, i.e. 31.3% lower demands on distribution-transportation capabilities;
- following a reduction of the available distribution capacity within the 4-tier supply chain by 10%, the degree of non-functionality of the main cross-docking centres was approximately 10%, but in the case of 3-tier supply chains, part of the disruption could be absorbed, and their blocked capacity was approximately 7.17%, which shows their ability to absorb 2.8% of malfunctions only due to their appropriate structure and location;
- at the same time, when the availability of transport and storage capacities of the supply chain was reduced to the level of 90% of the optimized chain, the 3-tier supply chain was able to absorb possible disruptions and spread them over smaller periods of time, thereby increasing the absorption capacity of the system and thus its overall resilience.

The research confirms hypothesis H1, that shorter distances could lead to higher efficiency for supply chain with fewer elements, both under optimal conditions and also if potential disruptions decrease the available capacity to 90% of the optimized level. It was proved that creating an additional cross-docking centre did not improve resilience in the case of the malfunction of supply chains, even though one may imagine that a depot close to the market or additional inventory would increase resilience. Based on these results, it would be appropriate to verify the given findings concerning 3-tier and 4-tier chains, completely or at least partially, on real data. At the same time, it would be appropriate to try to link the given findings to other important attributes of logistics analysis, such as, for example, cost and profitability analysis and ecological footprints.

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ORIGINAL PAPER

SUPPLIER ENVIRONMENTAL EVALUATION – THE RATIONALE FOR THE PRACTICAL APPLICATION

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ABSTRACT. Background: Reducing negative environmental impacts is becoming more and more significant in many areas of management. It is related not only to introducing the concept of circular economy, but also to building and integrating closed-loop supply chains. It includes different aspects of buyer-supplier relationships, such as supplier selection and evaluation. The aim of this article is to determine the scope of use of supplier environmental evaluation and the possibilities for the development of this concept.

Methods: The focal study has an exploratory character. The research methods used are the review of the literature and a survey conducted using the computer-aided telephone interview (CATI) technique. The reviewed literature is related to the areas of supplier environmental evaluation and supplier assessment. The empirical study focusses on different areas of supplier environmental evaluation and supplier assessment environmental criteria using a novel approach not found in the literature.

Results: The results refer to the possibilities of practical application of the supplier environmental evaluation. One of these possibilities is to link different areas of supplier environmental evaluation with specific environmental criteria of supplier assessment.

Conclusions: The main implication for business is to focus activities related to reducing negative environmental impacts mainly on the compliance of the supplier with the buyer's needs and requirements related to the environmental performance and limiting environmental impacts. The originality of this article lies in the approach focussing on differentiation between the environmental assessment and the environmental evaluation of suppliers and determining the possibility of a practical application of SEE.

Keywords: supplier environmental evaluation, supplier assessment, buyer-supplier relationships, buyer-supplier cooperation

INTRODUCTION

Supplier evaluation is an increasingly complex management problem. Companies face numerous problems regarding cooperation with their suppliers, including turbulent economic environment, supply chain disruptions resulting from the COVID-19 pandemic, and political shifts, e.g., resulting from the Russian invasion of Ukraine. Another significant factor is the increasing role of limiting negative environmental impacts, which is related to raising awareness of climate change, sustainable development, corporate social responsibility, and ESG reporting.

The aim of this article is to determine the scope of use of supplier environmental evaluation (SEE) and the possibilities for the development of this concept. Determining the value of environmental activities and supplier results could be crucial for achieving ESG goals [Whitelock, 2015] and building circular (or closed-loop) supply chains [Chen and Tan, 2021; González-Sánchez et al., 2020].

The paper is structured as follows. First, the introduction including the theoretical background is presented. Second, the materials and methods used in the conducted study are characterised. The results and discussion are then outlined. Finally, the conclusion including

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limitation, implications, and recommendations for future research are described.

The originality of this article lies in the approach that focusses on the differentiation between environmental assessment and SEE, and the determining possibility of the practical application of SEE.

SUPPLIER EVALUATION VS. SUPPLIER ASSESSMENT

Various scholars describe supplier evaluation differently, but they mostly define it in relation to assessment. Most of the definitions outlined in Table 1 link the supplier evaluation to their assessment.

Particular researchers consider the concept of evaluation more broadly than the assessment itself [Johnson et al., 2011; Monczka et al., 2016; Urbaniak, 2010; Zeydan et al., 2011]. Some of them consider supplier assessment as a measurement of supplier performance intended to provide a baseline for supplier evaluation and development [Monczka et al., 2016]. Others associate the supplier assessment with their evaluation [Park et al., 2010].

Table 1. Overview of definitions of supplier evaluation

Authors (year)	Definitions of the supplier evaluation
[Timmerman, 1986]	Assessment of supplier performance
[Purdy and Safayeni, 2000]	Assessment of supplier processes on the basis of given criteria
[Park et al., 2010]	Evaluation of the supplier's value by measuring its capacity and performance
[Urbaniak, 2010]	Periodic assessment and the assessment of the impact of the cooperation with the supplier on the recipient company and on the supply chain
[Johnson et al., 2011]	A set of formal and informal activities that aim to choose a supplier or assess its performance and effectiveness
[Hald and Ellegaard, 2011]	Process of quantifying supplier performance
[Zeydan et al., 2011]	A decision-making problem related to the selection or assessment of a supplier, with the aim of minimising risk and maximising added value for the recipient company
[Osiro et al., 2014]	Identify the importance of the supplier's performance in relation to the expectations placed on it in order to improve its capabilities and the effectiveness of its operations
[Monczka et al., 2016]	A set of activities that aims to select a supplier or assess its performance and effectiveness
[Sosnowski, 2022]	A set of systematic and objective activities designed to assess the performance, capability, and effectiveness of the supplier, including initial assessment, periodic assessment, and the impact assessment of the cooperation with the supplier on the recipient company and the supply chain

Source: own elaboration.

As shown in Table 1, supplier evaluation is based on their assessment. Therefore, the concept of evaluation, in addition to the initial and periodic supplier assessment, also refers to an assessment of the supplier's performance in relation to the results obtained and the impact of buyer-supplier cooperation on the buyer's company and on the focal supply chain. Furthermore, both supplier evaluation and supplier assessment are examples of multi criteria decision making (MCDM) problems [Gupta et al., 2019; Sumrit and Srisawad, 2022].

The main objective of supplier evaluation is to determine the value of supplier activities in relation to performance [Park et al., 2010]. However, the purpose of supplier evaluation is described as a decision to begin, continue, or discontinue a cooperation with a supplier [Johnson et al., 2011] and determine supplier development activities [Weele, van, 2014]. Supplier evaluation is also recognised as an important part of supply chain management. It plays a key role in improving company competitiveness and influences the efficiency of supply chain operations [Dachyar and Maharani, 2019].

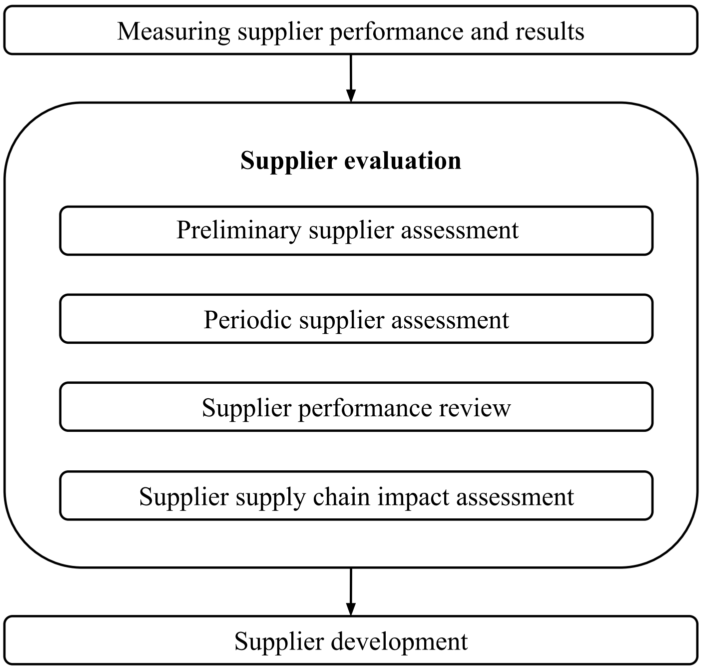

Fig. 1. Relationship between activity and performance measurement, assessment, evaluation, and supplier development
Source: own elaboration based on Monczka et al., 2016; Urbaniak, 2010; Weele, van, 2014

Supplier evaluation can be carried out during the duration of supplier cooperation or after it has ended. The start of cooperation with a supplier is determined by a positive result of the initial assessment – supplier selection [Urbaniak, 2010]. Some sources extend supplier evaluation to pre-cooperation activities [Hashemi et al., 2015].

INTRODUCING SUPPLIER ENVIRONMENTAL EVALUATION

According to J. Sarkis, the fundamental importance of environmental evaluation in the buyer-supplier relationships and in the context of other areas of evaluation is primarily due to the lack of control of the company over this particular area. Measurement as well as assessment and evaluation of suppliers are all concerned with the analysis of data and the identification of phenomena occurring. In this case, the data analysed relatively often comes from outside the company conducting the evaluation. Similarly, the identified phenomena also occur relatively often outside the focal company [Sarkis, 2014].

This leads to the problem of the lack of precise information received from the supplier and the lack of certainty about whether the information obtained from the supplier can be considered reliable [Sahu et al., 2012].

Based on Sosnowski [2022], the SEE can be defined as *'a set of systematic and objective activities designed to evaluate the performance, capability, and effectiveness of the supplier in the area of reducing various negative environmental impacts, including initial assessment, periodic assessment and impact assessment of the cooperation with the supplier in the recipient company and the supply chain.'*

Taking into account the definition given above, the following proposition was formulated:

P1. SEE determines whether to start or continue cooperation with suppliers.

There is a difference between supplier evaluation criteria focused on specific indicators and measures, such as price, delivery time, or number of late deliveries, and evaluation areas that relate to broad business components, such as performance or operational flexibility. This type of approach reflects, among other things, the 'green supplier evaluation index system' outlined by Sahu et al. [2012, 2014].

They assume a breakdown of the elements of the SEE system into three 'indexing levels', representing the levels of detail of the evaluation elements: the target level, the rule level, and the hierarchy level (see: Table 2).

Table 2. Example of green supplier evaluation index

Indexing levels	Indexing elements
Target level	SEE
Rule level	Areas of SEE, e.g., supplier capabilities, scope of cooperation, environmental factors
Hierarchy level	Criteria for assessing suppliers, e.g., delivery delays, level of carbon emissions into the atmosphere, implementation of an ISO 14001-compliant environmental management system

Source: own elaboration based on Sahu et al., 2012, 2014

According to this system, the supplier evaluation represents the target level that the company aims to achieve. The next level, known as the rule level, represents the areas of supplier evaluation. These include areas of supplier performance and buyer-supplier cooperation, such as supplier capabilities, scope of cooperation, or environmental factors. On the other hand, the lowest level, known as the hierarchy level, is represented by the individual assessment criteria assigned to the individual evaluation areas.

As such, the subdivision of the evaluation areas can provide a means of allocating the assessment criteria, where each evaluation area is assigned its associated supplier assessment criteria. The supplier evaluation system proposed by Dachyar and Maharani [2019], among others, is consistent with this approach.

MATERIALS AND METHODS

The focal study has an exploratory character and consisted of the following stages:

1. Review of the literature.
2. Preparation of the CATI (Computer-Assisted Telephone Interview) study;
3. Conducting the CATI study;
4. Analysis of results, including the semi-quantitative analysis of areas of SEE and environmental criteria in supplier management.
5. Formulating conclusions.

The preparation of the CATI study was preceded by a review of the literature on the topics of supplier assessment (including environmental criteria) and SEE. The study was carried out in a group of 101 medium and large companies operating in the following production sectors in Poland: chemical, pharmaceutical, IT and optical equipment, electrical, automotive, and furniture production. The size of the company and the production sectors were used in the quota sampling. The choice of industries was based on the relatively high level of environmental impact they generate. Including only medium and large companies resulted from the approach that the bigger the company, the more complex the management system it has implemented. The size of the company was determined by the number of employees. A medium company employs between 50 and 249 employees, while a large company employs at least 250. To choose the focal companies, the Polish Classification of Economic Activities (pl. *Polska Klasyfikacja Działalności*) was used.

The following research questions were formulated:

1. Do companies use environmental criteria in supplier assessment?
2. Do companies conduct SEE?

To answer these questions, the questionnaire was structured in order to gather the following information on the focal companies.

Q1 The main area of activity of the company.

Q2 The size of the company.

Q3 Conducting a formal initial or periodic supplier assessment.

Q4Using environmental criteria in initial or periodic supplier assessment.

Q5 Conducting SEE.

Q6 Using specific areas of SEE.

Q3 and Q5 are the filter questions. Data collection using the questionnaire is illustrated in Fig. 2.

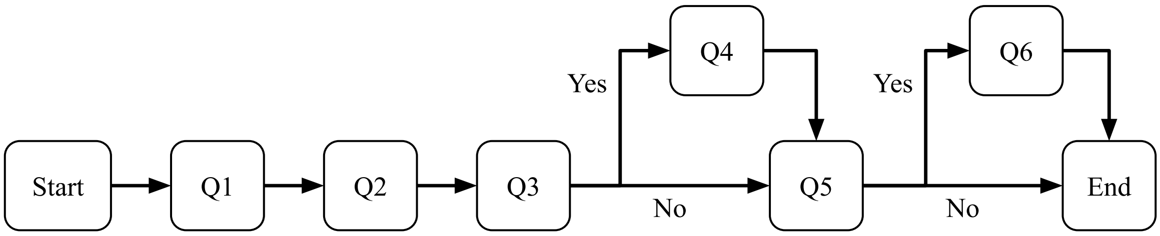

Fig. 2. Order of the questions in the questionnaire
Source: own elaboration.

The questionnaire preparation methodology was based on the assumption that reliable answers for Q4 and Q6 can only be given by respondents working for companies using environmental criteria in supplier assessment and conducting SEE.

RESULTS AND DISCUSSION

The environmental criteria for supplier assessment can be identified as those criteria that have a direct impact on their negative environmental impacts. It is important to note that environmental criteria can be related to both the level of negative environmental impact, e.g., the level of pollutant emissions [Wu and Barnes, 2016], and its reduction, e.g., waste reduction [Agarwal and Vijayvargy, 2012].

To carry out the study, the classification of environmental criteria was developed for supplier evaluation, based on the work of different scholars. It is presented in Table 3.

Table 3. Environmental criteria for supplier assessment

Environmental criteria for supplier assessment	Authors
Location of the supplier's plant	Dai and Blackhurst, 2012; Winter and Lasch, 2016
Having an implemented environmental management system, e.g., ISO 14001 or EMAS	Govindan et al., 2015; Shen et al., 2013; Tundys, 2018; Winter and Lasch, 2016
Use of environmentally friendly materials (e.g., recycled packaging)	Agarwal and Vijayvargy, 2012; Dai and Blackhurst, 2012; Govindan et al., 2015; Shen et al., 2013; Winter and Lasch, 2016
Use of environmentally friendly technologies (e.g., low-waste technologies)	Dai and Blackhurst, 2012; Govindan et al., 2015; Shen et al., 2013; Winter and Lasch, 2016
Reducing the consumption of material resources, energy, and water	Dai and Blackhurst, 2012; Govindan et al., 2015; Shen et al., 2013; Tundys, 2018; Winter and Lasch, 2016
Reducing pollutant emissions (waste, wastewater, atmospheric emissions, and noise)	Agarwal and Vijayvargy, 2012; Dai and Blackhurst, 2012; Govindan et al., 2015; Nielsen et al., 2014; Shen et al., 2013; Winter and Lasch, 2016

Source: own elaboration.

Types of emissions whose levels and reduction are used as criteria for supplier assessment include solid waste, wastewater, atmospheric emissions, odour, and hazardous substances [Nielsen et al., 2014]. Controlling the use of resources, for example, water, energy, and raw materials, is also a criterion of this type [Tundys, 2018]. Other environmental criteria include, for example, the use of pro-environmental raw materials and technologies in production, eco-design [Shen et al., 2013], the use of environmental labels, the use of recycled raw materials and the consumption of semifinished products, and energy and water [Govindan et al., 2015; Winter and Lasch, 2016].

Different scholars provide different classifications of environmental criteria for supplier assessment that overlap each other. For example, Dai and Blackhurst [2012] distinguish the 'minimise waste' criterion, which is directly related to both reducing the consumption of material resources, energy and water and reducing pollutant emissions (waste, wastewater, atmospheric emissions, and noise).

The diverse approaches of researchers to classifying the areas of SEE raise the question: which approach to this classification should be adopted in order to meet its primary objective, which is to assess the supplier's activities, capabilities, and effectiveness in reducing the various types of negative environmental impact [Sosnowski, 2022]? To answer this, it may be helpful to use the evaluation areas for development assistance by the Organisation for Economic Cooperation and Development. These areas are the following: impact, efficiency, effectiveness, relevance, coherence, and sustainability. The OECD uses the term 'criterion' for the evaluation [OECD, 2021, 2022]. However, in the context of this article, this term is restricted for assessment and the term 'area' is used instead.

Previously, there was no coherence area in this classification [OECD, 1991]. However, this new criterion complements the areas of SEE used, among others, by Sosnowski [2022] (see: Table 4).

Table 4. Evaluation areas by the OECD and proposed areas of SEE

Evaluation areas by OECD	Areas of SEE
Impact - the extent to which the intervention has generated or is expected to generate significant positive or negative, intended or unintended, higher-level effects	Supplier environmental impact - the changes that suppliers' activities have had on the environment
Coherence – the compatibility of the intervention with other interventions in a country, sector, or institution	Compliance of supplier environmental performance with the buyer's requirements
Efficiency – the extent to which the intervention delivers or is likely to deliver results in an economic and timely way.	Translating supplier activities into environmental outcomes
Effectiveness – the extent to which the intervention achieved or is expected to achieve, its objectives, and its results, including any differential results across groups.	Achieving by suppliers their environmental goals
Relevance – the extent to which the intervention objectives and design respond to beneficiaries	Compliance of supplier environmental performance with the buyer's needs
Sustainability - the extent to which the net benefits of the intervention continue or are likely to continue.	Sustainability of the supplier's environmental performance
-	Innovativeness of supplier environmental activities

Source: own elaboration based on OECD, 2021, 2022; Sosnowski, 2022.

This use of OECD evaluation areas is supported by the second principle of their use: 'The criteria should be applied thoughtfully and adapted to the context of intervention and evaluation. Although originally developed for use in international development cooperation, the criteria can be applied in any sector and for evaluations of public or private interventions. They can be used to evaluate many different topics and types of interventions, including thematic topics or strategic issues, policies, and projects [OECD, 2021].

Environmental efficiency as an area of environmental evaluation has been proposed by Govindan et al. [2015]. Environmental impact directly translates into reduction of its negative environmental impact, which is the objective of SEE as defined earlier. The sustainability of supplier environmental performance is consistent with the definition of sustainable development, of which environmental issues are one of the cornerstones [World Commission on Environment and Development, 1987].

The author expanded the classification of SEE areas to include innovativeness, which has been identified as SEE by, among others, Bai and Sarkis [2014], Hashemi et al. [2015], and Kannan et al. [2015].

With areas formulated in this manner, supplier evaluation can use supplier assessment to achieve its objective, depending on the preferences or environmental policy of the focal company. Supplier evaluation can be conducted in terms of, for example, the environmental impact of their activities, the contribution of their activities to reducing negative environmental impacts, or the achievement of their environmental goals.

Based on the proposed evaluation areas, the preferred supplier profile can be defined from an environmental evaluation point of view. It should meet the following requirements [OECD, 2021, 2022]:

1. Compliance of environmental performance with buyer needs;
2. Compliance of environmental performance with buyer requirements;
3. Minimal or no negative impact on the environment;
4. Achieving environmental goals;
5. Willingness to cooperate in reducing negative environmental impacts;
6. Conducting environmental activities that contribute to a sustainable reduction of negative environmental impacts;
7. Implementation of innovative environmental measures.

Fulfilling these requirements would increase the probability of a positive outcome of conducted SEE. The significance of these requirements could be determined by the CATI study. The structure of the survey group is presented in Table 5.

Table 5. Structure of the survey group

The main area of operations*	The main source of capital	Employment volume		Grand Total
		250 and more	From 50 to 249	
AUTO	Domestic	5	17	**22**
	Foreign	6	3	**9**
	Total	11	20	**31**
CHEM	Domestic	10	27	**37**
	Foreign	5	3	**8**
	Total	15	30	**45**
IT	Domestic	3	15	**18**
	Foreign	4	3	**7**
	Total	7	18	**25**
Grand Total		**33**	**68**	**101**

*AUTO – automotive production; CHEM – chemical, pharmaceutical, and plastic production; IT – IT, electronic, and electrical production.
Source: own elaboration

The numbers of companies in the studied sectors are similar to each other. No less than 25% of the companies studied in every sector were large companies that employ 250 or more people. Most of the companies studied conduct a formal initial or periodic supplier assessment, or both types (see Table 6).

Table 6. Conducting a formal initial or periodic supplier assessment

Conducting a formal initial and periodic supplier assessment	Number	Percentage
Initial assessment	17	16.8%
Periodic assessment	4	4.0%
Both	39	38.6%
None	41	40.6%
Total	**101**	**100%**

Source: own elaboration

More than 40% of the companies studied use environmental criteria in supplier selection and supplier assessment. Most of them use this kind of criteria in both supplier selection and supplier assessment (see Table 7).

Table 7. Using environmental criteria in supplier assessment

Using environmental criteria in the initial or periodic supplier assessment	Number	Percentage
Yes, in initial assessment	11	10.9%
Yes, in periodic assessment	3	3.0%
Yes, in both	27	26.7%
No	60	59.4%
Total	**101**	**100%**

Source: own elaboration

The most widely used criterion in both initial and periodic supplier assessment is having an implemented environmental management system. Other significant criteria in the initial supplier assessment are the use of environmentally friendly materials and technologies, while other significant criteria in the periodic supplier assessment are the use of environmentally friendly materials and the location of the supplier's plant(see: Table 8).

25.7% of the respondents indicated conducting SEE (see: Table 9).

Table 8. Using environmental criteria in supplier assessment: breakdown analysis

Using environmental criteria in supplier assessment	Abbreviation	Initial assessment		Periodic assessment	
		Number	Percentage	Number	Percentage
Having an implemented environmental management system, e.g., ISO 14001 or EMAS	C1	20	52.6%	16	51.6%
Use of environmentally friendly materials (e.g., recycled packaging)	C2	20	52.6%	12	38.7%
Use of environmentally friendly technologies (e.g., low-waste technologies)	C3	20	52.6%	11	35.5%
Location of the supplier's plant	C4	13	37.6%	12	38.7%
Reducing the consumption of material resources, energy and water	C5	13	37.6%	9	29.0%
Reducing pollutant emissions (waste, wastewater, atmospheric emissions, noise)	C6	9	24.7%	7	22.6%
Total of environmental criteria in the given type of supplier assessment		**38**	**100%**	**31**	**100%**

Source: own elaboration.

Table 9. Conducting SEE

Conducting SEE	Number	Percentage
Yes	26	25.7%
No	75	74.3%
Total	**101**	**100%**

Source: own elaboration.

Among the companies surveyed, the most frequently used evaluation area is the compliance of supplier environmental performance with the buyer's requirements. The second most frequently used area is the compliance of supplier environmental performance with the buyer's needs. The element of suppliers' activities was also taken into account here. The next areas most frequently used by respondents are the supplier environmental impact, suppliers achieving their environmental goals, and supplier activities translating into environmental outcomes. These evaluation areas determine the importance in a given company of translating supplier activities into results.

The areas indicated least frequently were the innovativeness of supplier environmental activities and the sustainability of the supplier environmental performance. This may be due to the dynamic nature of the supplier environmental performance, which varies over time.

The scope of using SEE areas is illustrated in Table 10.

Table 10. Using areas of SEE

Areas of SEE	Abbreviation	Number	Percentage
Compliance of the supplier’s environmental performance with the buyer's requirements	A1	16	61.5%
Compliance of the supplier’s environmental performance with the buyer's needs	A2	13	50.0%
Supplier environmental impact - the changes that suppliers' activities have had on the environment	A3	11	42.3%
Achieving by suppliers their environmental goals	A4	8	30.7%
Translating supplier activities into environmental outcomes	A5	7	27.2%
Innovativeness of supplier environmental activities	A6	4	15.4%
Sustainability of the supplier’s environmental performance	A7	3	11.5%
Total of using areas of SEE		**26**	**100%**

Source: own elaboration.

The results related to the compliance of the supplier’s environmental performance with the buyer’s requirements and needs indicate the relevance of the difference between these areas. In contrast to the requirements, the buyer’s needs might be difficult to measure. For example, to what extent should the focal company use environmentally friendly materials (C2) to meet the buyer’s needs?

To illustrate the relevance of specific environmental criteria in supplier assessment for specific areas of SEE, the cross-tabulation of these two entities was prepared (see: Table 11). This kind of approach was not found in the reviewed literature.

The cross-tabulation data was divided into three ranges:

1. >=10 – most relevant criterion for the SEE area;
2. 10> and >=5 – medium relevant criterion for the SEE area;
3. >5 – less relevant criterion for the SEE area.

Only one area (A1) is in range 1. for any criteria (C1, C2, and C3). This might indicate that these criteria are the most important for this particular area. The same criteria are in range 2. for A2, A3, and A5. Furthermore, the criteria C1, C2, and C3 are used the most frequently, while the areas that are used the most frequently are A1, A2 and A3. Moreover, only areas A1, A2, A3, and A5 are in the range 1. or 2. for more than 3 criteria.

Table 11. Cross-tabulation using areas of SEE and environmental criteria in supplier management

Environmental criteria in supplier assessment ➔ **Areas of SEE 🡻**	C1	C2	C3	C4	C5	C6	**Total of using given area of SEE**
A1	10	12	10	4	7	5	**16**
A2	6	8	8	2	8	4	**13**
A3	7	8	7	3	5	5	**11**
A4	3	5	6	4	4	1	**8**
A5	5	7	5	3	5	2	**7**
A6	2	2	3	2	2	2	**4**
A7	2	2	3	1	3	2	**3**
Total of using a given environmental criterion in ANY type of supplier assessment (initial or periodical)	**25**	**22**	**22**	**17**	**14**	**10**	

Source: own elaboration.

CONCLUSION

The main limitation of this study is that it only focuses on companies operating in Poland. However, the companies that were the main source of capital for both domestic (77) and foreign (24) were taken into account. The number of companies that conduct SEE – 26 out of 101, giving 25.7% of the sampling group – is also a limitation of this study. In the previous similar study conducted under the same conditions with respect to the population [Sosnowski, 2022], the percentage of companies conducting SEE was 63.8% (88 of 138). It gives a difference of more than 38 percentage points. Possible reasons for this difference include conducting the earlier study before the COVID-19 outbreak and before the Russian invasion of Ukraine.

The main implication for business is to focus activities related to reducing negative environmental impacts mainly on the compliance of the supplier with the buyer's needs and requirements related to the environmental performance and limiting environmental impacts. Such activities should primarily include implementing environmental management systems, e.g., ISO 14001 or EMAS, using environmentally friendly materials (e.g., recycled packaging) and using environmentally friendly technologies (e.g., low-waste technologies).

Taking into account the given limitations of the conducted study, the main recommendation for future research is to use ranges for the empirical study related to both using environmental criteria in supplier assessment and conducting SEE. Such ranges could include the Likert scale on the relevance of using specific environmental criteria and/or areas of SEE. Another recommendation for future research is developing supplier segmentation framework that takes into account SEE.

In summary, SEE is related to performing activities designed to assess the performance, capability, and effectiveness of the supplier in reducing various negative environmental impacts. These areas mainly include the compliance of the supplier with the buyer's needs and requirements related to the environmental performance and limiting environmental impacts. The criteria related to these activities should include implementing environmental management system, e.g., ISO 14001 or EMAS, using environmentally friendly materials (e.g., recycled packaging) and using environmentally friendly technologies (e.g., low waste technologies).

Although the scope of SEE use is limited, the future study might determine the relevance of this concept as an applicable, coherent, and standalone tool for decision-making related to supplier selection and evaluation.

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ORIGINAL PAPER

ADAPTATION OF SUPPLY CHAIN MANAGEMENT METHODS WITHIN REVERSE SUPPLY CHAINS OF WOOD BIOMASS

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ABSTRACT. Background: This paper is devoted to identifying supply chain management methods applicable within reverse supply chains of wood biomass. In general, sustainable supply chains are characterised by increased process efficiency. Reverse supply chains also require proper management. Hence it is necessary to verify the applicability of existing management methods and tools within chains of this type. This article is devoted to identifying management methods and tools that have the potential to be used in reverse supply chains of wood biomass. Particular emphasis was placed on the well-known green supply chain management approach (GrSC), the concept of Zero Waste Management, the product life cycle (LCA), cost-effectiveness, and environmental efficiency. The possibility of adopting the available methods in reverse wood biomass supply chains has been analysed with reference to the limitations and opportunities resulting from the methods used.

Methods: The research was divided into two stages. In the first stage, an in-depth argumentative literature review (ALR) was performed to identify methods and tools suitable for implementation within reverse supply chains of wood biomass. The second stage outlined boundaries and possibilities for implementing management methods within reverse supply chains of wood biomass.

Results: The study indicated the potential to implement available management solutions in reverse supply chains of wood biomass. However, it is necessary to consider the specificity of wood biomass material flows and the characteristic elements of supply chain infrastructure they require.

Conclusions: The results show that sustainable supply chain management methods are suitable for use in reverse supply chains of wood biomass. It is necessary to consider the specific characteristics of wood biomass and the location of its acquisition points in existing supply chains. A number of limitations, related to the availability of data, their quality, the location of biomass sourcing locations and processing centres, and the degree of integration of internal processes resulting from the size of the company dealing with wood biomass processing, are identified.

Keywords: reverse supply chains, wood biomass, reverse logistics, wood biomass management

INTRODUCTION

Supply chain management methods have to take into account the constraints associated with handling a specific type of goods. In the first step, these constraints must be identified. The role of reverse supply chains is constantly growing due to their possible contribution to the reduction of carbon footprints. Hence a proper method of calculating carbon footprints is essential to obtain an accurate emissions record for reverse distribution supply chains [Dubisz et al., 2022]. Wood biomass is indicated as a way to reduce CO2 emissions. According to the conducted research, based on the example of the 27 European community members, using wood biomass as a reused raw material can significantly contribute to the reduction of greenhouse gas emissions. This illustrates the significant role of wood biomass as a raw material in European economies [Shabani and Sowlati, 2013]. Wood biomass has relatively low logistic requirements. With proper storage conditions in terms of temperature and humidity, wood biomass can be successfully used to produce active carbon, which can purify and separate chemical-origin impurities, as shown in

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tests [Danish and Ahmad, 2018]. Research has shown that the proper location of accumulation centres and processing facilities in the reverse wood waste supply chain can affect its efficiency. Mathematical modelling that considers the effect of process scalability can affect a supply chain's efficiency level [Egri et al., 2021]. The sustainable supply chain management approach is similar to the management of reverse supply chains of wood biomass in terms of its capacity to increase efficiency in the consumption of renewable resources and minimise the environmental carbon footprint of processes. The readiness to optimise a network should be precisely verified based on known and validated methods. Contemporary supply chains are based on the principles of sustainable development [Werner-Lewandowska and Golinska-Dawson, 2021]. This approach is also supported by the conception of triple bottom line reporting (3BL), taking into consideration the sole profit of an enterprise and social and environmental perspectives [Kleindorfer et al., 2009]. Simultaneously, other researchers have pointed out the advantage of lean management (LM) methods when implementing green supply chain management (GrSCM) solutions. Research on increasing environmental efficiency in reverse supply chains using LM tools focuses on production processes and transport [Zhu and Sarkis, 2004]. Nevertheless, the optimisation of GrSCM could be used within reverse supply chains to mitigate their environmental impact. Influencing the shape of the supply chain by indicating the optimal location of process participants impacts the efficiency of the entire reverse supply chain of wood biomass. For this purpose, Langarian heuristic algorithms can be introduced to obtain an optimised supply chain design [Elhedhli and Merrick, 2012]. It can be observed that supply chains identified as production and transport are subject to similar optimisation trends and management methods [Kara et al., 2007]. A similar SC management approach is noticeable in wood pellet supply chains [Mobini et al., 2013]. Due to similar goods specificity, most findings from research on production and transport may be introduced within biomass reverse supply chains. As a result, wood biomass reverse supply chain design should be considered in terms of coherence with transportation and production optimisation processes. Hence, in modelling the design of reverse supply chains of wood biomass in a similar way to standard supply chains, their environmental performance is analysed to minimise their environmental impact [Mobini et al., 2013; Murphy et al., 2014]. Research shows that the basis for a well-configured and designed reverse supply chain design may be proper management of change and risk in a business. In order to achieve total efficiency in the supply chain, it is necessary to ensure proper supply chain visibility (SCV). Difficulties in maintaining the correct identification of the quality of processes are also the subject of research in scientific analyses [Freichel et al., 2022].

Given the similarities related to the management of sustainable supply chains and reverse wood biomass supply chains, the primary logistic parameters have to be identified. The current research is tailored to the specific characteristics of wood biomass, so the obtained results have a practical character.

An effective logistic model of wood biomass has to consider key logistics parameters and predict each identified parameter's impact on its effectiveness.

The aim of this article is to identify existing management methods and accompanying tools suitable for use in reverse supply chains of wood biomass. The need to verify the possibility of their use results from the specificity of wood biomass and the shape of the supply chains supporting its flows. Using a suitable method or management support tool requires consideration of the specificity of the organization of flows of a given commodity, in this case, wood biomass. It is also necessary to properly understand the mechanisms determining the method's effectiveness. For this purpose, it is necessary to precisely identify the available approaches and verify their applicability and limitations.

This paper is divided into three main sections and a conclusion containing research findings and a proposal for further research. In the first section, a literature review is conducted. The overarching aim is to verify other research and its scope to ensure the novelty of the current research. In this step, emphasis is placed on identifying the main methods used to optimise reverse supply chains. In the next step, the appropriate tools used in the indicated methods are verified. The primary goal of this study is to identify the main methods and tools used to optimise reverse supply chains that can be adopted within reverse supply chains of wood biomass. Considering wood biomass's physical form and specificity, at the end of the research, in the Conclusions and Recommendations section, an attempt is made to indicate probable methods suitable for implementation in reverse biomass supply chains.

Based on the existing literature, the following research questions have been formulated:

Research Question 1 (RQ1): Is it possible to implement known and widely used methods of reverse supply chain management, considering the specificity of wood biomass?

Research Question 2 (RQ2): Are there any limitations in managing the wood biomass supply chain resulting from its specific characteristics?

For the literature review in this publication, the argumentative literature review (ALR) guidelines proposed by McCullough et al. [2004] were used. For this purpose, a research area was first identified: supply chain management methods and tools that would be suitable for use within reverse supply chains of wood biomass. The next step was to conduct a comprehensive literature review, during which the limitations associated with using the identified methods were demonstrated. In the next step, based on the conducted study, several limitations in the identified methods which may significantly interfere with their use were demonstrated. On this basis, further conclusions were also formulated.

The research methodology applied in this research is presented in Fig. 1.

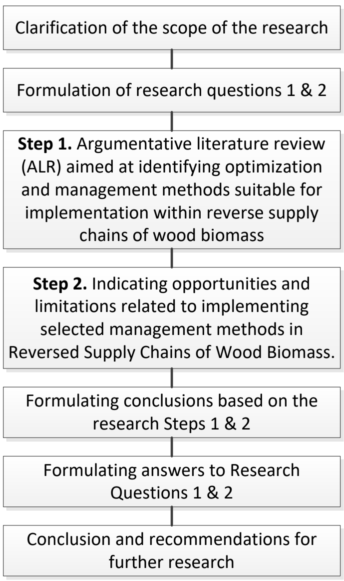

Fig. 1 Course of the research applied in this study.
Source: own elaboration

LITERATURE REVIEW

Following the adopted ALR method, the literature review identified various approaches to managing and optimising reverse supply chains. To commence a review, the Scopus and Google Scholar databases were used during the study. The keywords that were used included: "reverse supply chain", "optimisation of reverse supply chains", "supply chain management", and "operational management of supply chains".

In order to conduct the study, the following inclusion criteria were adopted:

- Articles published in English in a defined research area
- Articles on the research area published in the years 2011–2021
- Simultaneously the following exclusion criteria were defined:
    - Publications describing non-product-specific methods within supported supply chains were excluded.
    - Articles referring to the use of various different management methods whose effectiveness for wood biomass it would be impossible to verify were also excluded.

Twenty-six papers describing the results of research on supply chain management were identified. Eleven articles from 2011–2021 relating to research on chain management methodologies were divided into five categories: green supply chain management, cost-effect approach, LCA approach, environmental efficiency, and the concept of zero waste management. The following 16 articles were used to determine the possibilities and boundaries for applying supply chain management tools within reverse supply chains of wood biomass. The method adopted for the literature review is presented in Fig. 2.

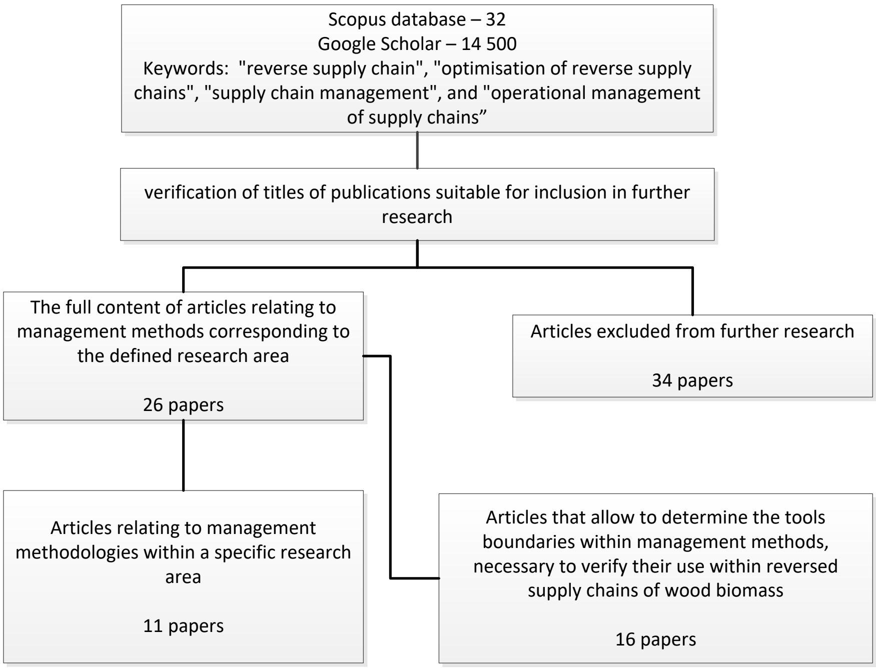

Fig. 2 Course of the argumentative literature review conducted within this study.
Source: own elaboration

A number of challenges related to the management of supply chains have been outlined in various scientific studies [Zhu and Sarkis, 2004; Barbosa-Póvoa, 2009; Mobini et al., 2013; Freichel et al., 2022]. For example, an organisation's success is not only due to profits but also to its resource management approach, striving to maintain the sustainable development of its processes and care for people and the planet's future [Barbosa-Póvoa, 2009]. A management approach dedicated to the transport organisation of wood biomass supply must reflect the specificity of the primary goods transported within the supply chain. Based on other scientific research, several common challenges were pointed out. Those mainly related to operational running costs, organisation of the reverse supply chain and energy consumption [Morrissey and Browne, 2004]. The common denominator for various approaches seems to be the determination of the economic size of the delivery [Condeixa et al., 2022].

Another approach to the management of reverse logistics chains indicates the need to ensure a short transportation or production lead time, flexibility, and economic efficiency. Using the best-worst method (BWM) and the innovative concept of comprehensive distance-based ranking (COBRA), a Multi-Criteria Decision Making (MCDM) organisational model was created that considers the functional needs identified above [Krstić et al., 2022]. There are also noticeable barriers to quick access to information due to a company's financial capabilities. Large international enterprises can obtain advanced IT tools, enabling efficient information management within the supply chain. Smaller companies, which include companies related to the production, transport, and management of wood biomass flows, can use shared solutions. This approach indicates the potential to minimise the costs associated with logistics services and should be considered when managing reverse supply chains of wood biomass [Kawa, 2012].

Simultaneously, there is a need to define a precise logistics model that provides complementary reverse logistics services considering the specificity of the transported product [Brown, 2021]. For this purpose, it is necessary to determine the influence of individual logistic parameters on the reverse supply chain's design, its bottlenecks and detailed result parameters outlining the quality of the logistics model in general. The accompanying supply chain should correspond to the entire product life cycle to maximise the benefits of the company's operations. Hence an appropriate LCA approach needs to be reconsidered when designing the reverse supply chain [Cordella et al., 2008; Finnveden et al., 2009; Murphy et al., 2014]. Closed Loop Supply Chains (CLSCs) complement the concept of lean management and fit into the solutions specified in the Circular Economy [Govindan et al., 2015] The need for conscious optimisation of existing processes is also evident in this research area. Hence the multi-objective optimisation method can be supportive, especially in CLSCs [Amin and Zhang, 2012b; Barker and Zabinsky, 2011; Mogale et al., 2022].

Based on an analysis of the literature regarding challenges that reverse supply chains of biomass may face, many similarities with other reverse logistics chains can be identified. Another study points out the importance of product specificity in supply chain design in the case of the natural gas supply chain [Dujak et al., 2019]. The parameters to be assessed are the same when organising the transport of wood biomass [Danish and Ahmad, 2018]. It is essential to check how the available methods can be suitably implemented in existing reverse supply chains. The aspect of biomass flow organisation should be considered.

Based on the literature analysis, there have been many studies on the efficiency of supply chains, and some of their methods could be implemented in the qualitative assessment of wood biomass return processes. However, the research gap still consists in determining the degree of dependence on individual parameters of the supply chain and their impact on the design of a reverse wood biomass supply chain. According to waste management models, the LCA approach is the most important. The importance of the LCA assessment method within reverse supply chain management has been outlined in various studies [Morrissey and Browne, 2004; Mukherjee et al., 2020]. Researchers point out multiple difficulties that may occur while modelling a reverse supply chain for different sorts of waste [Abejón et al., 2020; Murphy et al., 2014]. In Abejón et al., the heterogeneous nature of research on Municipal Solid Waste (MSW) is pointed out, which provides a better perspective for the design of reverse logistics chains, taking into consideration the specific details of a product (or waste). In other research related to the LCA approach in reverse supply chains, the arrangement of other supporting processes is shown to be crucial for maintaining proper goods flow [Rehl and Müller, 2011].

An approach pointing to the environmental efficiency of global reverse supply chains (GRSC) is also worth noting. One study analyses quantitative models [Seuring, 2013]. Other researchers point to the importance of properly defining the location of raw material collection points within the chain, measuring and managing carbon dioxide emissions related to logistics processes and global challenges affecting the shape of supply chains [Egri et al., 2021; Tao et al., 2018]. Another study focuses on sea transport and cost-effectiveness resulting from fluctuating exchange rates [Xu et al., 2017].

A reverse supply chain management approach based on the concept of the circular economy is consistent with the desire to minimise the amount of waste sent to landfill. According to the idea of Zero Waste (ZW) management, waste is a resource that should be adequately processed, managed, and reused. The proposed approach also points to the synergy of LCA and the maximisation of process efficiency in GRSC [Gaur et al., 2022]

IDENTIFICATION OF SUPPLY CHAIN MANAGEMENT TOOLS

Based on the analysis of the literature, the main factors determining the shape of reverse supply chains and influencing their effectiveness were identified:

- The cost-effect approach that determines the economic viability of the applied design [Wang et al., 2019; Dev et al., 2020].
- The LCA approach, in which product life cycles are precisely defined, and the method of obtaining, processing, and reusing the product after the end of its life is determined [Morrissey and Browne, 2004; Mukherjee et al., 2020; Rehl and Müller, 2011].
- An environmental approach that verifies the quality of reverse processes in terms of their energy intensity and emissivity. This approach is also related to the planning of the reuse of product waste as a raw material in subsequent processes [Abdullah et al., 2018; Chen and Chen, 2017; Reddy et al., 2022].

The identified approaches recommended for managing reverse supply chains could be adopted within reverse supply chains of wood biomass. They are presented in Table 1.

Table 1. SC management approaches suitable for reverse supply chains of wood biomass

Identified methodologies	**Main research references**
Green supply chain management	[Seuring, 2013], [Xu et al., 2017]
Cost-effect approach	[Dev et al., 2020; Wang et al., 2019]
LCA approach	[Morrissey and Browne 2004; Mukherjee et al. 2020; Rehl and Müller 2011]
Environmental Efficiency	[Abdullah et al., 2018; Chen and Chen, 2017; Reddy et al., 2022]
The concept of Zero Waste Management	[Gaur et al., 2022]

Source: own elaboration.

MANAGEMENT BOUNDARIES WITHIN REVERSE SUPPLY CHAINS OF WOOD BIOMASS

Mathematical modelling can effectively support the supply chain design process. This approach shows implementation potential within the reverse supply chain of wood biomass [Brandenburg et al., 2014]. In other studies, the importance of defining the general framework in the context of the organisation of reverse supply chains is outlined as a significant supply chain design factor [Fleischmann et al., 1997]. The framework used for mathematical modelling should be used for distribution planning, inventory control and production planning. Each indicated element affects the result of the mathematical modelling of the reverse supply chain. The conclusions from these studies indicate the need for holistic planning of entire supply chains to maintain a sustainable framework for further optimisation of the reverse supply chain [Kannegiesser and Günther, 2014]. The approach presented in the research is consistent with the LCA management method, because it involves planning the entire life cycle of products. All the critical elements of every supply chain, such as manufacturing, goods collection, repairs, disassembly, recycling, and disposal, must be considered. Hence the related initial simulations must consider the specific characteristics of wood biomass management [Amin and Zhang, 2012a]. A lack of planning can affect the effectiveness of the reverse chain. Thus, proper support from mathematical modelling has to be employed in the supply chain design process.

According to the conducted research, various control parameters influencing overall model effectiveness were identified:

- The geographical locations of the significant processing centres within the supply chain [Tao et al., 2018; Redmer, 2022]
- Limitations resulting from the capacity of individual chain elements [Abdullah et al., 2018]
- The impact of changes in the supply chain and the impact of their application on the continuity of processes [Dahmus, 2014]
- The need for proper goods flow planning in order to maximise process efficiency while maintaining relatively low unit costs [Kolinski et al., 2017; Golinska-Dawson, 2019]

According to other researchers, management techniques based on the multi-criteria decision-making (MCDA) approach are among the most effective [Barker and Zabinsky, 2011]. This method considers various control parameters that may influence the reverse supply chain flow's overall effectiveness in terms of planning and management [Morrissey and Browne, 2004; Mukherjee et al., 2020].

Multi-criteria analysis can be used when modelling a reverse supply chain of wood biomass to select the best SC participants [Amin and Zhang, 2012b]. Obtaining the information required to conduct an analysis using this method is crucial for further mathematical simulation modelling within the chain. All the approaches indicated in the literature are used to optimise and simulate the most favourable scenario for handling biomass return flows [Kara et al., 2007]. The choice of management strategy must consider the organisation's goals, information flow, key resources, the level of integration of management processes, and holistic approaches to the analysis of internal and external factors. The chosen strategy also has to consider the balance between the goals and expectations of the stakeholders [Miller et al., 1996]. Hence, the Gray Stratified Decisions Model has potential for implementation when choosing the most suitable management method within reverse wood biomass supply chains [Mierzwiak, 2023].

A summary of the identified approaches is provided in Table 2.

Thepresented set of approaches is enhanced with a comment based on the analysed literature indicating potential limitations and possibilities of their use in handling reverse logistics chains of wood biomass.

The main obstacles that may prevent the use of management tools within reverse supply chains of wood biomass were also identified. During the research, data quality was identified as a major concern. Another element is the identification of mutual dependencies between the components in the model. Due to the specific characteristics of wood biomass, it may be impossible to control all centres responsible for obtaining biomass.

Based on the research, the identified supply chain management methods have the potential to increase the efficiency of wood biomass supply chains. What is more, the limitations related to the specific properties of wood biomass do not exclude their implementation.

CONCLUSIONS AND RECOMMENDATIONS

The identified management methods can all be used to increase the effectiveness of logistics processes. This can be seen as their common goal. However, each of the presented methods draws attention to different areas of logistics management in supply chains. The emphasis is variously placed on: supply chain participants' geographical location, product life cycle, environmental aspects, and waste minimization. Implementing elements of these management methods within reverse supply chains of wood biomass can achieve a synergy effect that benefits logistics processes.

Table 2. Boundaries and possibilities of management within Reverse Supply Chains of Wood Biomass.

Tools for the management of reverse supply chains of wood biomass	**Development boundaries for reverse supply chains of wood biomass**	**Possible directions for the development of wood biomass reverse supply chains**	**Main references**
Mathematical modelling	The limited amount of data sourced within the reverse supply chain of wood biomass, and its lower quality, can negatively affect the results of mathematical modelling.	The proposed approach of sharing IT tools among small and medium-sized enterprises could significantly affect the quality of data obtained for analysis [Kawa, 2012].	[Fleischmann et al., 1997; Amin and Zhang, 2012a; Kannegiesser and Günther, 2014; Egri et al., 2021]
Supply chain modelling regarding the correlation between logistics factors	The identification of dependencies between process participants may depend on the data quality, as in the case of mathematical modelling. Incorrect identification of dependencies can lead to wrong decisions.	By introducing advanced IT solutions, it is possible to track processes on an ongoing basis [Kawa, 2012]. Such a solution has the potential to improve data quality. Therefore, further analysis will support an accurate decision-making process.	[Zhu and Sarkis, 2004; Abdullah et al., 2018; Zapp et al., 2021]
Centre of gravity method for key process participants location	Due to the type of source from which biomass is obtained, it is not possible to fully control the sources within reverse chains. Forecasts play a crucial role in this area. Modelling of the supply chain to determine the centre of gravity can only indicate places of collective processing, cross docks and wholesale distribution points	A potential development direction for RSCWB is shortening the distance between the process participants. This can be achieved by combining the functionality of biomass acquisition, identification, processing and even distribution centres. The ideal solution would be to keep all the listed functionalities in the wood biomass harvesting centre – in the forest.	[Melo et al., 2006; Tao et al., 2018; Zomparelli et al., 2018; Redmer, 2022]
Multi-criteria decision making (MCDA)	In the case of small enterprises without a management hierarchy and procedures, the implementation of modern management methods may be too complex.	Based on the literature analysis, using MCDA management tools would allow for the optimal selection of service providers in the wood biomass reverse supply chain.	[Morrissey and Browne, 2004; Kara et al., 2007; Barker and Zabinsky, 2011; Amin and Zhang, 2012b; Mukherjee et al., 2020]

Source: own elaboration.

The conducted research permitted the identification of management methods from the perspective of the product – wood biomass. The identified methods make it possible to improve the efficiency of logistics processes in reverse supply chains. The publications, methods and corresponding tools analysed during the study did not consider the specific properties of wood biomass. In the conducted analysis, it was possible to verify their limitations and potential for further development from the wood biomass perspective. Management methods come with a set of recommendations for their adoption within supply chains. However, the specificity of a particular product, as in the case of wood biomass, requires managers to consider its characteristics, its places of acquisition, and its localization within current supply chains. Simultaneously, the quality and availability of data determine the actual shape of reverse supply chains. This perspective was verified during the study and supported the implementation of the identified methods and tools within reverse supply chains of wood biomass. The importance of mutual dependencies between reverse supply chain participants was identified as a major factor influencing overall wood biomass chain efficiency. It has been verified that proper management of logistics processes depends on actual logistics data quality and the capacity for processing and analysis focused on supply chain improvements. Simultaneously establishing the localization of each supply chain participant plays a crucial role in increasing the efficiency of reverse supply chains of wood biomass.

Answers to the research questions were obtained based on the conducted research. It has been shown that existing management methods are suitable for use in reverse supply chains of wood biomass. However, it is necessary to meet specific requirements related to the specific characteristics of wood biomass and elements of reverse supply chains, especially regarding the location of the participants responsible for the acquisition of raw materials and their processing. Limitations affect the choice of the appropriate supply chain management method. The identified boundaries are related to access to primary data and its quality. Other limitations are related to the specific location of biomass processing centres and their acquisition. Due to the relatively low level of complexity of enterprises responsible for handling reverse wood biomass supply chains, implementing advanced process management methods may be challenging. As a result of an in-depth literature study (ALR), it was shown that the LCA approach is crucial in modelling the design of reverse supply chains.

This study was limited to a literature review based on the Scopus and Google Scholar databases. Further research could be expanded to include other databases and include empirical research based on case studies. Simultaneously, research should be carried out to determine mutual statistical dependencies between various parameters of wood biomass reverse supply chains.

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ORIGINAL PAPER

DIGITALIZATION IN THE REVERSE SUPPLY CHAIN: A BIBLIOMETRIC ANALYSIS

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ABSTRACT. Background: This article analyzes scientific sources on the process of digitalization in the reverse supply chain. Its aim is to comprehensively investigate and analyze the transformative potential of digitalization in the context of the reverse supply chain. By exploring the utilization of digital technologies such as the Internet of Things (IoT), data analytics, artificial intelligence (AI), and blockchain, the study aims to uncover opportunities for enhancing the efficiency, sustainability, and environmental responsibility of reverse supply chain processes. A significant number of studies on this topic have been published in scientific journals such as *Sustainability*, *Business Strategy and the Environment* and the *International Journal Of Production Economics*. The most cited authors were identified, including Gupta and Yu. Among the main countries where such research has been conducted are China, the United States, the United Kingdom, India and Pakistan.

Methods: The study included a literature review, evaluation, analysis and mapping, which allowed the authors to identify certain trends. The Scopus database was used for this purpose, and the selected articles were analyzed using MS Excel and VOSviewer. Initially, 297 documents were identified, and 82 articles remained after exclusions.

Results: The findings of the study emphasize the growing interest in this topic, the increasing number of related scientific publications, and the importance of the sustainable use of resources in the reverse supply chain.

Conclusions: The relevance of this study lies in the possibility of optimizing the processes of the reverse supply chain, ensuring the rational use of resources and achieving sustainable development. The application of the results obtained could be useful for a wide range of industries, including the activities of enterprises and the formation of policies for the management and development of economic sectors.

Keywords: digitalization, reverse supply chain, blockchain, digital transformation, Internet of Things, circular economy

INTRODUCTION

Blockchain technology's growing influence extends to the economy and various facets of human life [Kouhizadeh and Sarkis 2018], with the reverse supply chain emerging as a pivotal realm for digital integration [Rane and Thakker 2020]. Digital technologies' potential to optimize these processes carries significant implications for the economy, environment, and society [Bekrar et al. 2021].

Kouhizadeh and Sarkis [2018] delve into blockchain's supply chain role, underscoring its favorable impact on sustainability. Factors like trust, traceability, and transparency are key, as noted by Centobelli et al. [2022]. Rane and Thakker [2020] examine industry challenges that blockchain and the IoT can help address by enhancing supply chains and boosting competitiveness.

The Internet of Things (IoT) has a significant impact on the supply chain, particularly the reverse supply chain. Parry et al. [2016] discuss the IoT's role in gathering consumer product data, while proposing a management framework. IoT adoption also facilitates the transition to a circular economy

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[Ingemarsdotter et al. 2019, Charnley et al. 2019] by means of strategies such as tracking, monitoring, and design evolution [Ingemarsdotter et al. 2019]. Gu and Liu [2013] explore the IoT's potential in reverse logistics management, introducing a data-driven closed-loop system.

Tang et al. [2022] study the impact of blockchain and Industry 4.0 on the circular economy, describing how it enhances enterprise efficiency. Their research underscores blockchain's potential for ecological production and processing within the circular economy. Additionally, Khan et al. [2021b] illustrate how blockchain and Industry 4.0 facilitate circular economy adoption, emphasizing improved environmental and financial efficiency for enterprises following circular economy principles.

Hrouga et al. [2022] propose the use of blockchain and IoT integration to digitize the reverse supply chain, ensuring reliability. Shambayati et al. [2022] suggest virtual supply chains (VSC) to tackle enterprise challenges, finding IoT integration enhances VSC profitability.

Sarkis et al. [2021] explore digitalization's role in sustainable environmental supply chains, affirming its positive impact on the green supply chain. Eldrandaly et al. [2022] assert that blockchain and Big Data Analytics (BDA) promote cleaner production and social responsibility. Terrada et al. [2022] highlight the IoT's importance in supply chain management. Khan et al. [2021a] show blockchain's influence on environmental and operational enterprise performance.

Wu and Zhao [2022] introduce green reverse logistics as a method to enhance environmental protection and resource utilization in enterprises. They highlight blockchain's role in boosting profits and environmental impact. Fiorini et al. [2022] investigate information technology's contribution to green supply chains, emphasizing its impact on environmental and financial efficiency. Long et al. [2022] study blockchain's effect on green supply chain efficiency, noting its influence on supply chain trust.

Bekrar et al. [2021] explore blockchain's potential to enhance reverse logistics (RL) within the circular economy. Krstić et al. [2022c] highlight the inadequacy of traditional approaches for modern supply chain demands and propose Industry 4.0 technologies like the IoT and cloud computing to improve reverse logistics and circular economy development. De Giovanni [2022] underscores blockchain's advantages for circular economy advancement, including transparency, traceability, visibility, and security, resulting in enhanced enterprise efficiency.

Rane et al. [2021] emphasize environmental sustainability's importance in supply chain management for green supply chain development. The integration of blockchain and the IoT stands as a pivotal factor in fostering this development. Mubarik et al. [2021] investigate blockchain's influence on green supply chain practices, revealing its positive impact on environmental practices, demand and supply planning, reducing overproduction, and enhancing cost savings. Feng et al. [2022] identify green supply chain innovation (GSCI) as an innovative approach on the part of manufacturers that uses digital technologies to incorporate environmental concerns into their supply chain management. Implementing digital technologies enhances green supply chain management (GSCM) performance by improving internal environmental management, green procurement, customer collaboration, inventory recovery, and eco-design.

Scholars also highlight the positive influence of supply chain digitalization on social welfare. For instance, Wang et al. [2022] contend that incorporating blockchain technology into supply chains enhances waste recycling and elevates social welfare levels within enterprises. Economic improvements are also realized due to blockchain implementation. Krishna et al. [2022] emphasize enhanced productivity and customer satisfaction resulting from supply chain digitalization. Yang et al. [2022] illustrate how enterprises adopt advanced IT technologies, like AI and blockchain, to ensure robust supply chain operations, leading to IT development and positive impacts on supply chain and enterprise sustainability.

Tseng et al. [2022] assert that digitalization and reverse supply chain practices enhance sustainable efficiency and enterprise benefits. Munir et al. [2022] highlight blockchain's positive impact on economic, environmental, and social performance. Ma and Hu [2022] underline blockchain's role in optimizing supply chains, boosting economic, social, and environmental outcomes. Pratapa et al. [2022] explore digital solutions for enhancing environmental sustainability in enterprises. Digital technology integration catalyzes enterprise transformation.

Difrancesco et al. [2022] describe blockchain's influence on supply chain performance and transformation. Ijuin et al. [2021] affirm digitalization's positive effect on supply chain management and environmental concerns.

Papanagnou's [2022] article addresses the intricacies of closed supply chains, highlighting the IoT's potential to mitigate inventory-related costs and disruptions. Kazancoglu et al. [2022] establish blockchain's role in enhancing supply chain resilience. Pathak et al. [2022] explore supply chain digitalization for optimization and positive outcomes.

Sutawijaya and Nawangsari [2020] examine environmental management in supply chains, revealing the substantial influence of Industry 4.0 on green supply chain implementation. Gayialis et al. [2022] advocate for an Industry 4.0-based system to enhance service supply chain management. Krstić et al. [2022a] confirm that modern foreign technologies enhance logistics efficiency.

Potential barriers can impede the adoption of blockchain technology and other digital tools in supply chains. Bajar et al. [2022] classify obstacles into operational, strategic, technical, financial, infrastructure, and governmental categories for blockchain implementation. Yu et al. [2022] investigate blockchain's influence on environmental concerns and the global supply chain, highlighting its potential to offer security, transparency, and traceability solutions.

However, the study of the impact of digitalization on the reverse supply chain still requires a more detailed analysis and study of various aspects of this process. With this in mind, the purpose of this article is to study the role of digitalization in the reverse supply chain, as well as to analyze its impact on various aspects of the economy, including efficiency, sustainability, innovation, and competitiveness. The research aims to answer the following questions: (i) Which academic publications have the greatest impact on reverse supply chain digitalization? (ii) Which authors are leading in publishing research on this topic? (iii) In which countries is there a particular interest in research on reverse supply chain digitalization? (iv) What are the main topic categories covered by research in this area? (v) How often are papers related to the digitalization of the supply chain cited? (vi) What are the most commonly used terms when analyzing research on the relevant topic?

The contribution of this article, which distinguishes it from other studies, is as follows: (1) This study contributes to the literature on the digitalization of the reverse supply chain. (2) The study reflects the processes of digitalization of the reverse supply chain in various industries, showing their importance, and therefore increasing the level of efficiency of logistics processes.

The rest of the manuscript is organized as follows: Section 2 presents the methodology for searching and analyzing publications on the digitalization of the reverse supply chain. Section 3 presents the results of the analysis and scientific mapping. It lists the most representative journals, authors, countries, institutions and organizations, subject categories, citations, and key terms. Section 4 contains a discussion of the research results. Section 5 contains conclusions, a discussion of the study’s limitations, and potential avenues for future research.

MATERIALS AND METHODS

The bibliometric analysis investigates publications related to the digitalization of the reverse supply chain. This approach includes productivity analysis and network analysis applied to a dataset retrieved from the Scopus database to identify collaborations between authors, organizations, and countries. This study developed a search for documents related to digitalization in sustainable supply chains to identify studies relevant to the topic. The search terms were based on the digitalization of the reverse supply chain, as shown in Table 1. Use of the SCOPUS database was selected as the search strategy because SCOPUS is a prestigious and significant repository for research of high importance and global relevance.

Table 1. List of keywords used for the literature search

Groups	Search for items
Digitalization	"digitalization" OR "digital transformation" OR "digital technologies" OR "digital innovation" OR "digital supply chain" OR "digital strategy" OR "digital society" OR "Blockchain" OR "Blockchain technology" OR "Internet of Things"
Reverse supply chain	"reverse supply chain" OR "reverse logistics" OR "closed-loop supply chain" OR "CLSC" OR "closed loop supply chain" OR "closed-loop supply chain management" OR "remanufacturing" OR "green supply chain"
Searched Equation	TITLE-ABS-KEY ("digitalization" OR "digital transformation" OR "digital technologies" OR "digital innovation" OR "digital supply chain" OR "digital strategy" OR "digital society" OR "Blockchain" OR "Blockchain technology" OR "Internet of Things") AND TITLE-ABS-KEY ("reverse supply chain" OR "reverse logistics" OR "closed-loop supply chain" OR "CLSC" OR "closed loop supply chain" OR "closed-loop supply chain management" OR "remanufacturing" OR "green supply chain") AND (EXCLUDE (AFFILCOUNTRY,"Russian Federation")) AND (LIMIT-TO (DOCTYPE,"ar")) AND EXCLUDE (PUBYEAR,2023)) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (SUBJAREA,"BUSI") OR LIMIT-TO (SUBJAREA,"ECON") OR LIMIT-TO (SUBJAREA,"SOCI") OR LIMIT-TO (SUBJAREA,"DECI") OR LIMIT-TO (SUBJAREA,"ENVI"))

The search of the Scopus database yielded two hundred and ninety-seven (297) documents. Certain articles were selected for research and analysis using four filters. The main stages of the selection process are shown in Figure 1.

The first filter concerned the exclusion of articles published in or related to the Russian Federation. This decision was made in light of the war and aggression launched by Russia against Ukraine. As a result, 8 articles were excluded.

At the next stage (using the second filter), all publications other than articles were excluded: reviews, conference papers, book chapters, books, etc. As a result, 146 publications were excluded and 145 articles were obtained.

The third filter removed articles published in 2023 and not in English (25 such articles were found).

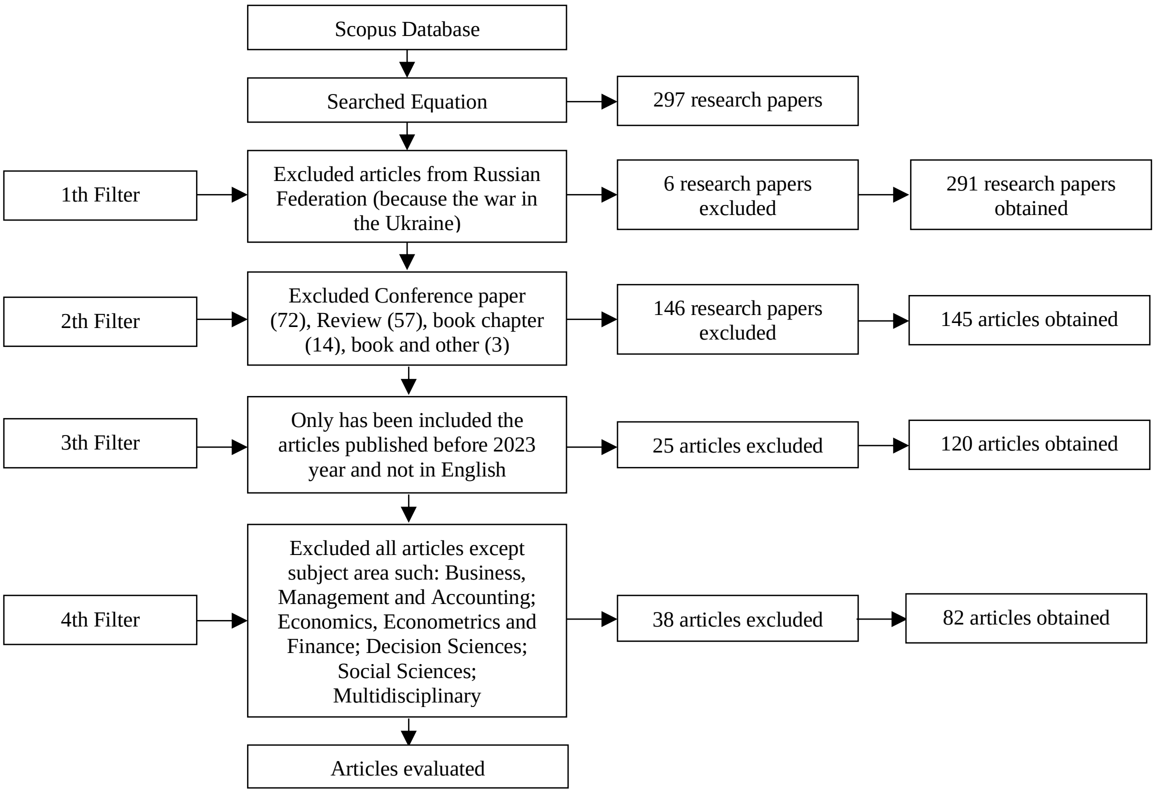

Fig. 1. Research methodology.

The fourth filter excluded subject areas that were not relevant to the research area. As a result of this filter, 38 articles were excluded. After applying this last filter, 82 articles were obtained, on the basis of which the main study was conducted.

The obtained articles were downloaded to MS Excel for analysis and visualization of information using VOSviewer software.

RESULTS

Publications by year

This study examines articles published over the past ten years, from 2013 to 2022. The number of documents per year is depicted in Figure 2. The number of publications began to increase in 2017, with the peak observed in 2022, with 37 articles. The ARIMA model was employed to forecast the volume of documents and analyze publication trends. The forecast for future publications (from 2023 to 2033) is as follows: 40, 43, 46, 49, 52, 55, 58, 61. Considering alternative forecasts (positive and negative), we can assert that the predicted rate of growth in the number of future publications in this field varies.

Journals

A total of 82 articles were published in 44 journals. In general, this shows that interest in research on the digitalization of the reverse supply chain is gradually growing in academia. In terms of quantitative indicators, 34 journals (77%) published 1 article, 6 journals (14%) published 2–3 articles, and 4 journals (9%) published more than 4 articles.

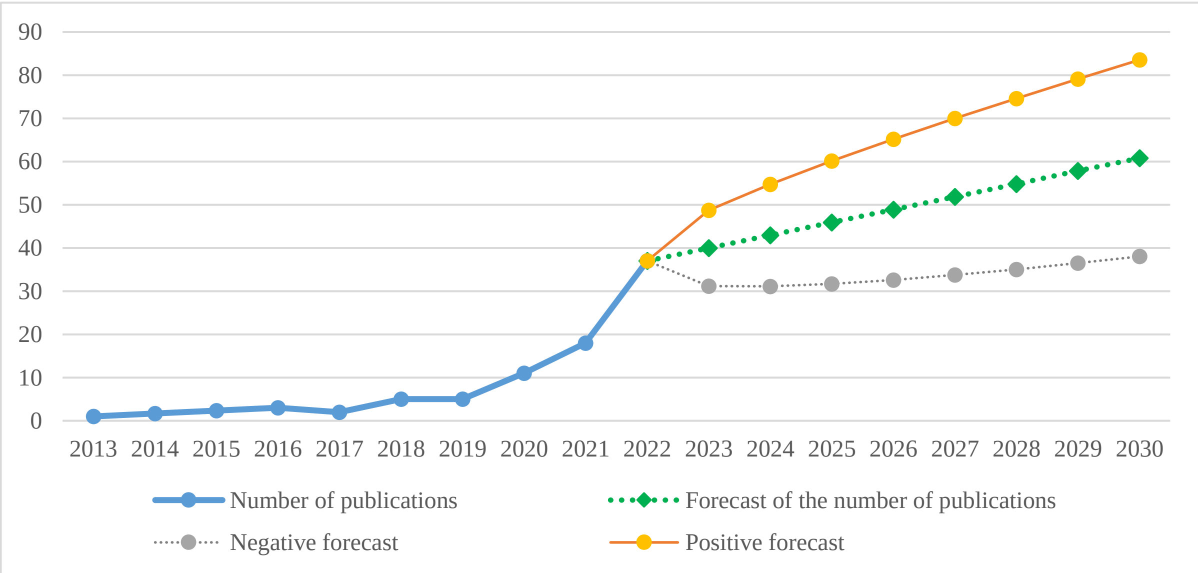

Fig. 2. Number of publications and cumulative total by year with a forecast until 2030.

In addition, the top 10 most productive journals in terms of the number of articles published on the digitalization of the reverse supply chain were identified. Table 2 shows the top 10 most productive journals, as well as information about the publisher, Scimago Journal Rank-SJR 2021 and H-index 2021, subject area and category.

The top 10 journals published 44 articles, which is 53.7% of the total number of articles in the study. Most articles were published in the journal Sustainability (16 articles), followed by Business Strategy And The Environment (5 articles), the International Journal Of Production Economics (5 articles), the Journal Of Cleaner Production (4 articles), Management Of Environmental Quality: An International Journal (3 articles) and Transportation Research Part E: Logistics And Transportation Review (3 articles).

Table 2. Top 10 most productive journals on the digitalization of the reverse supply chain

+++++++++++	Journal	Publisher	№ of Publ	SJR-2021	H-Index 2021	Subject Area and Category
1	Sustainability Switzerland	Multidiscipli-nary Digital Publishing Institute	16	0.664	109	Energy Engineering and Power Technology (Q2), Renewable Energy, Sustainability and the Environment (Q2), Environmental Science (miscellaneous) (Q2), Management, Monitoring, Policy and Law (Q2), Geography, Planning and Development (Q1)
2	Business Strategy And The Environment	Wiley-Blackwell	5	2.241	115	Business and International Management (Q1), Strategy and Management (Q1), Management, Monitoring, Policy and Law (Q1), Geography, Planning and Development (Q1)
3	International Journal Of Production Economics	Elsevier	5	2.808	197	Business, Management and Accounting (miscellaneous) Management Science and Operations Research (Q1), Economics and Econometrics (Q1), Industrial and Manufacturing Engineering (Q1),
4	Journal Of Cleaner Production	Elsevier	4	1.921	232	Strategy and Management (Q1), Renewable Energy, Sustainability and the Environment (Q1), Industrial and Manufacturing Engineering (Q1), Environmental Science (miscellaneous) (Q1)
5	Management Of Environmental Quality: An International Journal	Emerald Publishing	3	0.816	42	Biochemistry, Genetics and Molecular Biology (miscellaneous) (Q2), Management, Monitoring, Policy and Law (Q1), Public Health, Environmental and Occupational Health (Q2)
6	Transportation Research Part E: Logistics And Transportation Review	Elsevier	3	2.835	122	Business and International Management (Q1), Management Science and Operations Research (Q1), Civil and Structural Engineering (Q1), Transportation (Q1)
7	Annals Of Operations Research	Springer Nature	2	1.165	111	Decision Sciences (miscellaneous) (Q1), Management Science and Operations Research (Q1)
8	IEEE Transactions On Engineering Management	IEEE	2	0.881	97	Strategy and Management (Q2), Electrical and Electronic Engineering (Q1)
9	International Journal Of Physical Distribution And Logistics Management	Emerald Publishing	2	1.950	117	Management of Technology and Innovation (Q1), Transportation (Q1)
10	International Journal Of Production Research	Taylor & Francis	2	2.780	153	Strategy and Management (Q1), Management Science and Operations Research (Q1), Industrial and Manufacturing Engineering (Q1)

If we analyze the publishers, the top 10 journals include Elsevier (3 journals with 12 articles) and Emerald Publishing (2 journals with 5 articles).

The subject categories of the journals in SJR were: Business and International Management (Q1), Strategy and Management (Q1), Management, Monitoring, Policy and Law (Q1), Management Science and Operations Research (Q1), Geography, Planning and Development (Q1), Civil and Structural Engineering (Q1), Transportation (Q1). These subject categories have a citation indicator that is higher than the average for cited documents, indicating that the articles published in these journals have a high impact and are frequently cited.

Authors

The top 10 most productive authors with the highest number of publications were identified, as were those who most frequently appeared as the first author (Table 3). First place was taken by Gupta, USA, with four publications on the digitalization of the reverse supply chain, but he is not the first author of any of the publications. Yu, China, is in second place, also with 4 publications, but in one of them, he is the first author. Next are Khan and Krstić with 3 published articles, and in all 3 articles, they are the first authors. Sarkis has 3 publications but is the first author of only 1 article. Agnusdei, Miglietta and Tadić have 3 publications each but are not the first authors of any of them. Charnley has 2 published articles but is the first author of only 1 article. Hu has 2 published articles, but he is not the first author of either of them.

Table 3. Top 10 most productive authors on the digitalization of the reverse supply chain

No.	Name of Author	Country of Author	Number of Publications	Number of Publications as the First Author
1	Gupta, S.M.	USA	4	0
2	Yu, Z.	China	4	1
3	Agnusdei, G.P.	Italy	3	0
4	Khan, S.A.R.	China	3	3
5	Krstić, M.	Serbia	3	3
6	Miglietta, P.P.	Italy	3	0
7	Sarkis, J.	USA	3	1
8	Tadić, S.	Serbia	3	0
9	Charnley, F.	UK	2	1
10	Hu, J.	China	2	0

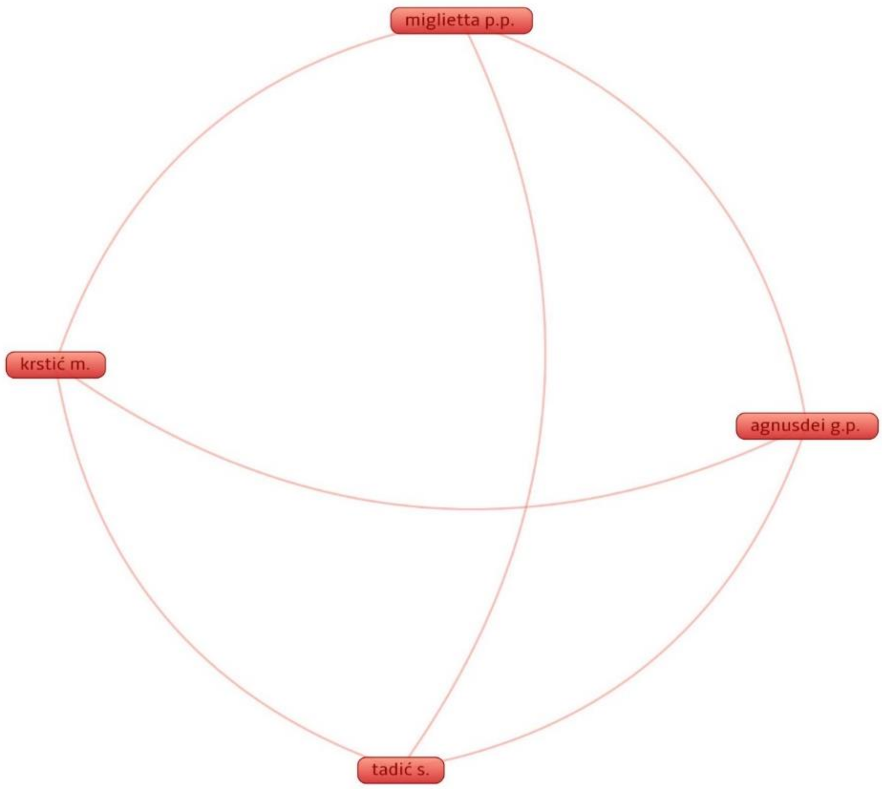

Fig. 3. Collaboration of authors in the study of the digitalization of the reverse supply chain (created with VOSviewer).

Countries, institutions, organizations

In terms of countries, the number of publications on the digitalization of the reverse supply chain was determined according to the Scopus database (see Figure 4). The study determined that the country with the largest number of publications is China, with 21 publications and 25.6% of the total analyzed articles. The United States is in second place with 16 articles (19.5%), followed by the United Kingdom, with 11 articles (13.4%), India, with 10 articles (12.2%), Pakistan, with 7 articles (8.5%), France and Italy, with 6 articles (7.3%), Sweden, with 5 articles (6.1%), and Finland and Malaysia, with 4 articles (4.9%).

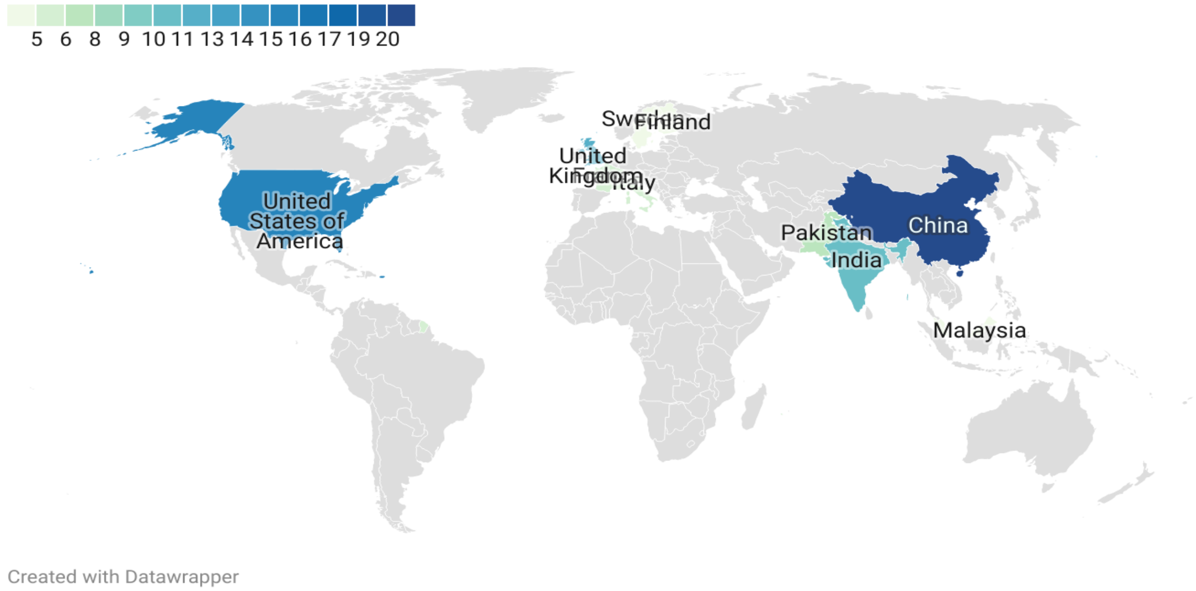

Fig. 4. Network of authors' cooperation in research on the digitalization of the reverse supply chain.

Figure 5 presents three correlation groups that show the extent of collaboration between authors from different countries on research articles. India, China, and Germany represent the clusters with the highest correlation due to the widespread collaboration of authors from these countries.

Figure 6 provides an analysis of cooperation between countries using density visualization.

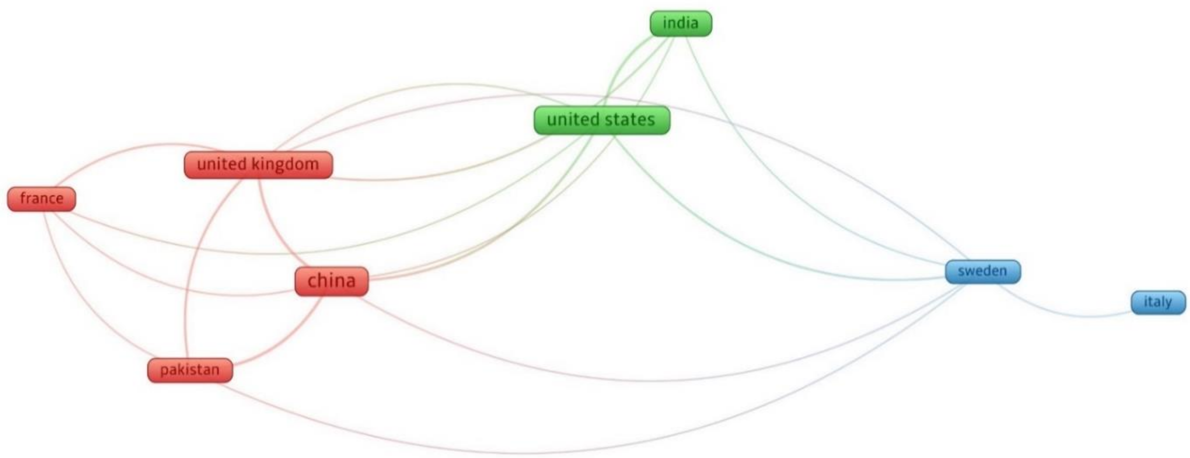

Fig. 5. Network of cooperation between countries in research on the digitalization of the reverse supply chain (created using VOSviewer).

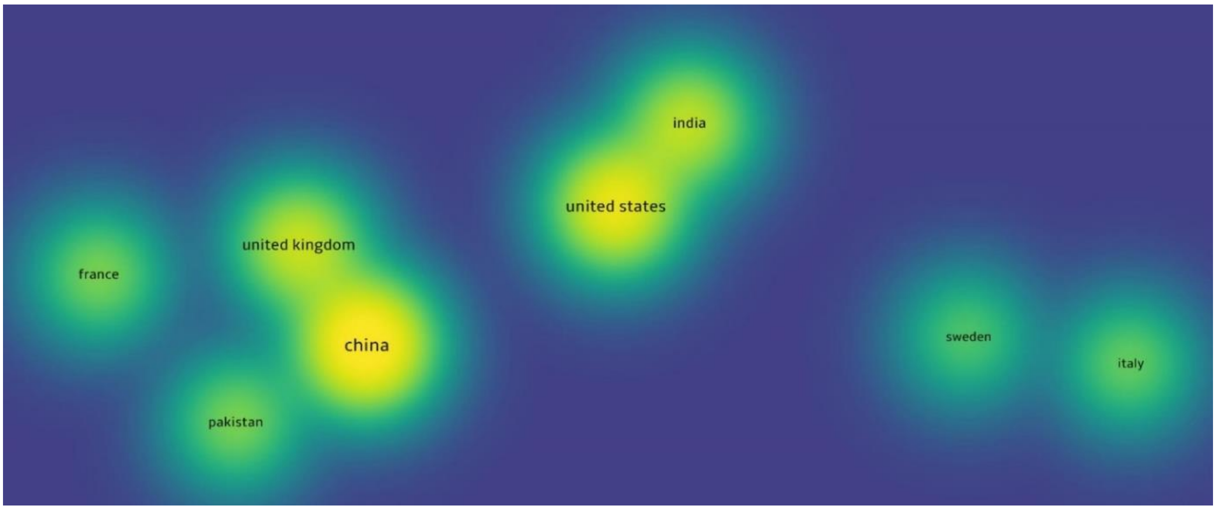

Fig. 6. Analysis of representative countries by topic over time with density visualization (created using VOSviewer)

The institutions and universities with the largest number of articles were also studied (see Table 4). Worcester Polytechnic Institute (USA), with 4 published articles, ranks first in the top 10. It is followed by Northeastern University (USA) and Chang'an University (China) with 4 publications each. The number of articles published by the universities and institutions in the top 10 (6% of the 160 institutions that published articles) accounts for 15.5% of the total number of articles published by all institutions worldwide. The remaining 84.5% were published by instutions that had only produced one (60.4%) or two articles.

Table 4. Top 10 most productive institutions in the digitalization of the reverse supply chain

No.	Funding	Country	Articles
1	Worcester Polytechnic Institute	USA	4
2	Northeastern University	USA	4
3	Chang'an University	China	4
4	Ministry of Education China	China	3
5	Universita del Salento	China	3
6	University of Belgrade	Serbia	3
7	Ilma University	Pakistan	3
8	Xuzhou University of Technology	China	3
9	The Business School	USA	3
10	Beijing Key Laboratory of Urban Spatial Information Engineering	China	2

Table 5 shows the 10 largest funding sources with the highest number of sponsored articles related to the digitalization of the reverse supply chain. The main funding sponsor is the National Natural Science Foundation of China, with 13 funded articles, which corresponds to 17% of all articles. The regions with the highest number of institutions sponsoring research related to the digitalization of the reverse supply chain are China, with 5 institutions, and the EU, with 2 institutions.

Table 5. Breakdown of items by financing entities

No.	Funding	Country	Articles
1	National Natural Science Foundation of China	China	13
2	Engineering and Physical Sciences Research Council	United Kingdom	4
3	Fundamental Research Funds for the Central Universities	China	4
4	European Commission	EU	3
5	Ministry of Education of the People's Republic of China	China	3
6	Basic and Applied Basic Research Foundation of Guangdong Province	China	2
7	Horizon 2020 Framework Programme	EU	2
8	Ministry of Higher Education, Malaysia	Malaysia	2
9	Ministry of Science and Technology, Taiwan	Taiwan	2
10	Research Grants Council, University Grants Committee	China	2

Analysis of subject categories

The analysis identified thematic categories in the research on the digitalization of the reverse supply chain (Figure 7). The results show that 44 articles (18.8%) were published on the topic of Business, Management and Accounting . The top 5 categories also include Engineering, with 38 articles (15.9% of publications), Environmental Science, with 37 articles (15.5% of publications), Social Sciences, with 34 articles (14.2% of publications), and Decision Sciences, with 24 articles (10% of publications).

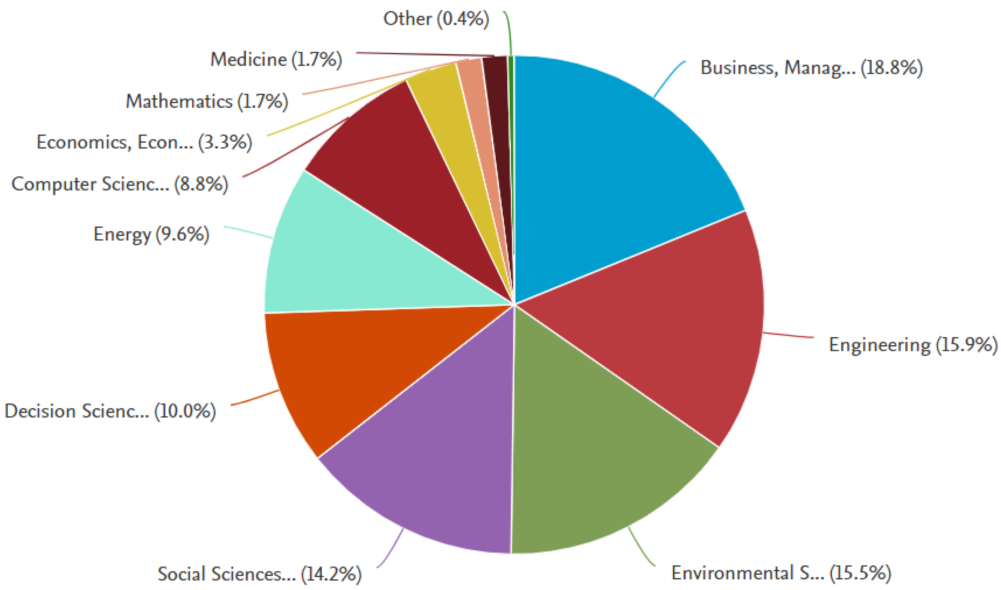

Fig. 7. Thematic categories in which articles on the digitalization of the reverse supply chain are most often published

Analysis of citations

The most cited articles are presented in Table 6. The table also shows the country, FWCI, Institution, SJR-2021, SDGs 2023, SciVal Topic, and main topic of each article. Kouhizadeh and Sarkis [2018] published the most cited article on the topic under study. Their paper discusses in detail the issues of green supply chains and blockchain technology. It has been cited 278 times, which corresponds to 12% of the total number of citations in the Top 10. Camacho-Otero et al. [2018] focused their research on the circular economy. This publication received 161 citations (7%). Khan et al. [2021] consider the role of blockchain technology in circular economy practices and its impact on the eco-environmental performance of an organization. The number of citations of this study is 127 (5%). Alcayaga et al. [2019] describe the relationship between the Internet of Things, business models, and the circular economy. This publication received 119 citations (5%). Centobelli et al. [2022] propose an integrated Triple Retry framework for the development of cyclic blockchain platforms. Their study has received 86 citations (4%).

Analyzing the SDGs, the main goals for research on the digitalization of the reverse supply chain are: 9 (Industry, innovation and infrastructure), 12 (Responsible consumption and production), 17 (Partnership for the goals), and 8 (Decent work and economic growth).

The analysis of citations by authors is shown in Figure 8.

Table 6. Top 10 publications with the highest number of citations on the digitalization of the reverse supply chain

No.	Authors Title	Times Cited (2014-2023)	FWCI	Institution	Country (1st Author)	Journal	SJR-2021	SDGs 2023 (Goal)	SciVal Topic
1	Kouhizadeh and Sarkis [2018] Blockchain practices, potentials, and perspectives in greening supply chains	278	11,55	Worcester Polytechnic Institute	USA	Sustainability	0.664	9,12	Bitcoin; Ethereum; Internet Of Things
2	Camacho-Otero et tl. [2018] Consumption in the circular economy: A literature review	161	8,14	NTNU Norwegian University of Science and Technology	Norway	Sustainability	0.664	9,12	Platforms; Collaborative Consumption; Peer to Peer
3	Khan et al. [2021b] Industry 4.0 and circular economy practices: A new era business strategies for environmental sustainability	127	20,59	Xuzhou University of Technology	China	Business Strategy and the Environment	2.241	9,12,17	Supply Chain; Environmentally Preferable Purchasing; Green Practices
4	Alcayaga et al. [2019] Towards a framework of smart-circular systems: An integrative literature review	119	6,36	Institute for Integrated Quality Design	Austria	Journal of Cleaner Production	1.921	9	Product-service Systems; Service Economy; Value Co-Creation
5	Centobelli et al. [2022] Blockchain technology for bridging trust, traceability and transparency in circular supply chain	86	38,56	University of Naples Federico II	Italy	*Information and Management*	2.558	9	Bitcoin; Ethereum; Internet Of Things
6	Parry et al. [2016] Operationalising IoT for reverse supply: the development of use-visibility measures	83	9,83	University of the West of England	United Kingdom	*Supply Chain Management*	2.385	9	Product-service Systems; Service Economy; Value Co-Creation
7	Zhang et al. [2018] The 'Internet of Things' enabled real-time scheduling for remanufacturing of automobile engines	82	3,93	Northwestern Polytechnical University	China	Journal of Cleaner Production	1.921	8,9, 12,17	Internet Of Things; Radio Frequency Identification Device; Shopfloor
8	Garrido-Hidalgo et al. [2020] The adoption of Internet of Things in a Circular Supply Chain framework for the recovery of WEEE: The case of Lithium-ion electric vehicle battery packs	81	4,43	Universidad de Castilla-La Mancha	Spain	*Waste Management*	1.741	7,12	E-Waste; Electronic Waste; Electronic Equipment
9	Khan et al. [2021a] Green data analytics, blockchain technology for sustainable development, and sustainable supply chain practices: evidence from small and medium enterprises	71	9,41	Xuzhou University of Technology	China	Annals of Operations Research	1.165	9,12,17	Supply Chain; Environmentally Preferable Purchasing; Green Practices
10	Alqahtani et al. [2019] Warranty and maintenance analysis of sensor embedded products using internet of things in industry 4.0	66	5,49	King Abdulaziz University	Saudi Arabia	International Journal of Production Economics	2.808	9	Warranty; Minimal Repair; Preventive Maintenance

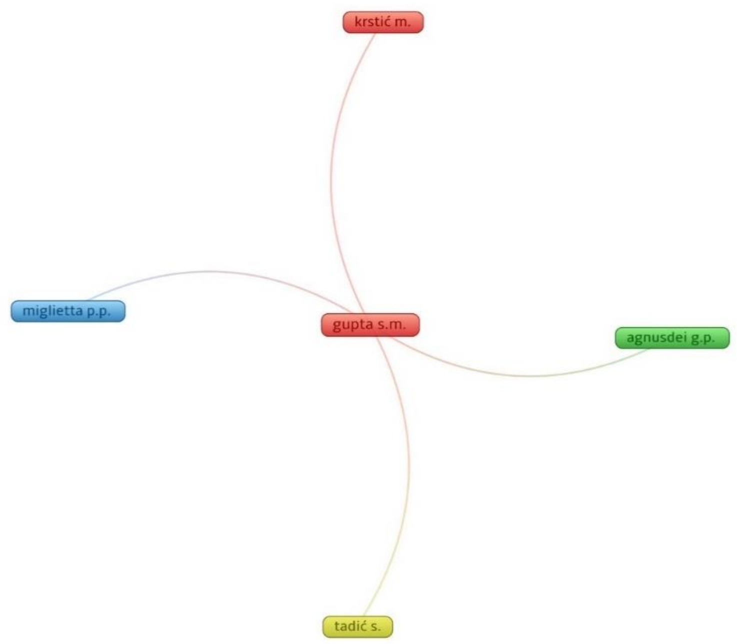

Fig. 8. Analysis of authors' citations in research on the digitalization of the reverse supply chain (created using VOSviewer).

The analysis of co-citations by cited authors makes it possible to identify four clusters. The results of the analysis are shown in Figure 9.

When looking at co-citations by cited sources, as shown in Figure 10, certain clusters can also be identified.

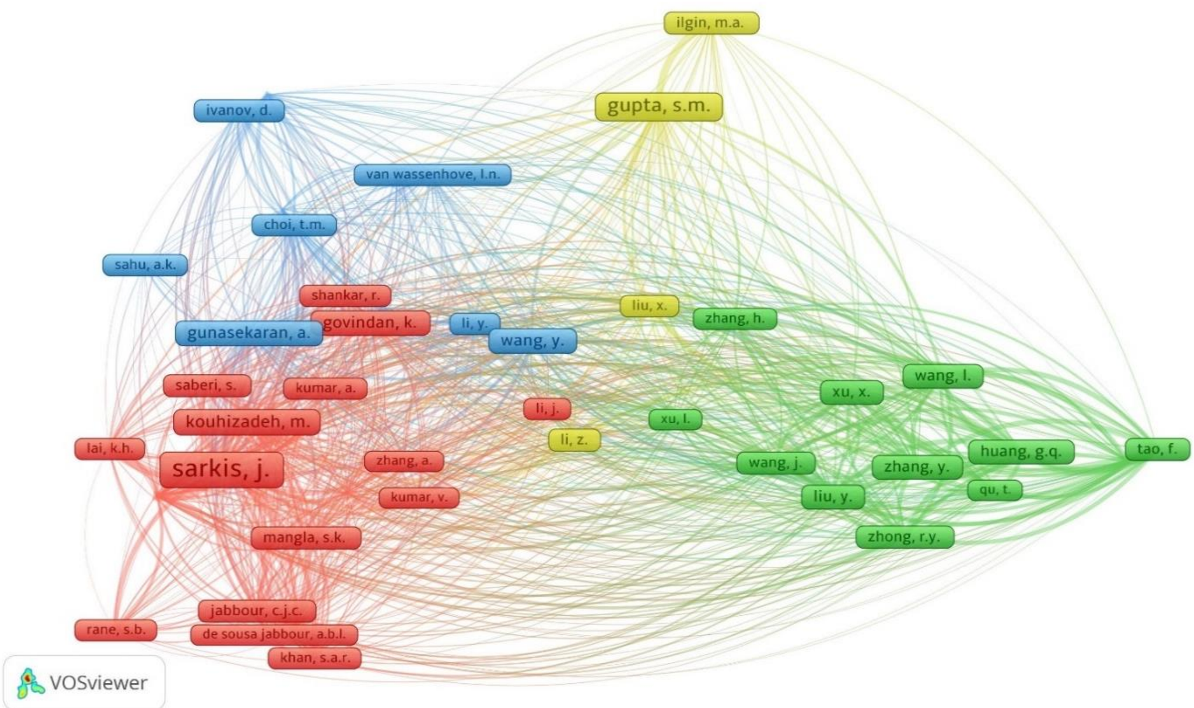

Fig. 9. Analysis of the most frequent co-citations in research on the digitalization of the reverse supply chain (created using VOSviewer).

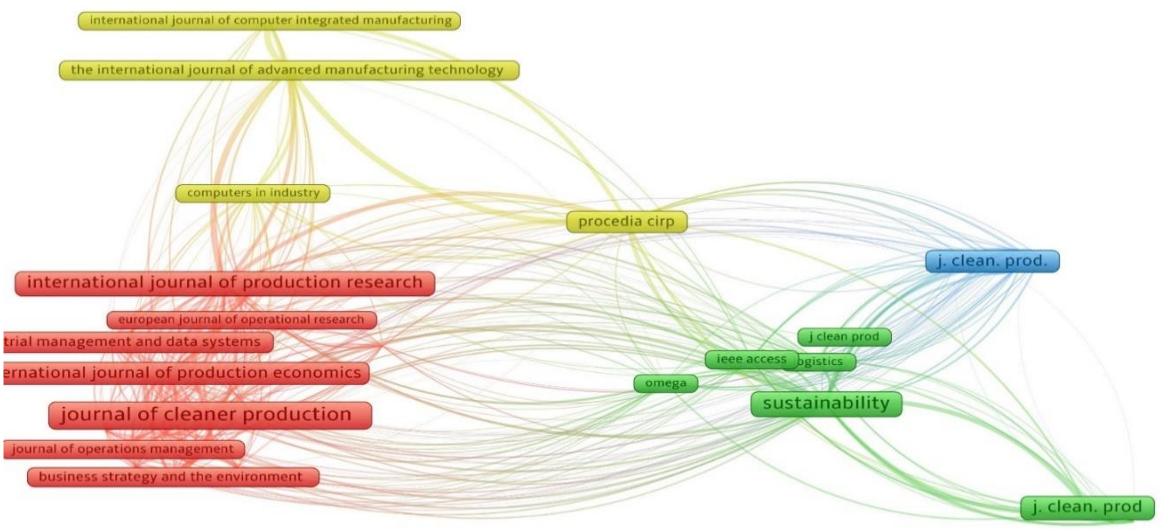

Fig. 10. Analysis of co-citation by cited sources in articles on the digitalization of the reverse supply chain (created using VOSviewer)

Analysis of terms

Analyzing the terms used in the titles and abstracts of manuscripts helps to identify areas of research on a given topic. Figure 11 shows the analysis of common usage for all words in the articles obtained using VOSviewer. The analysis identified three clusters. The first cluster is formed by such keywords as supply chain management and sustainable development. The second cluster contains the terms blockchain and closed-loop supply chain. The third cluster of words used in the selected articles is made up of circular economy, Industry 4.0, and Internet of Things.

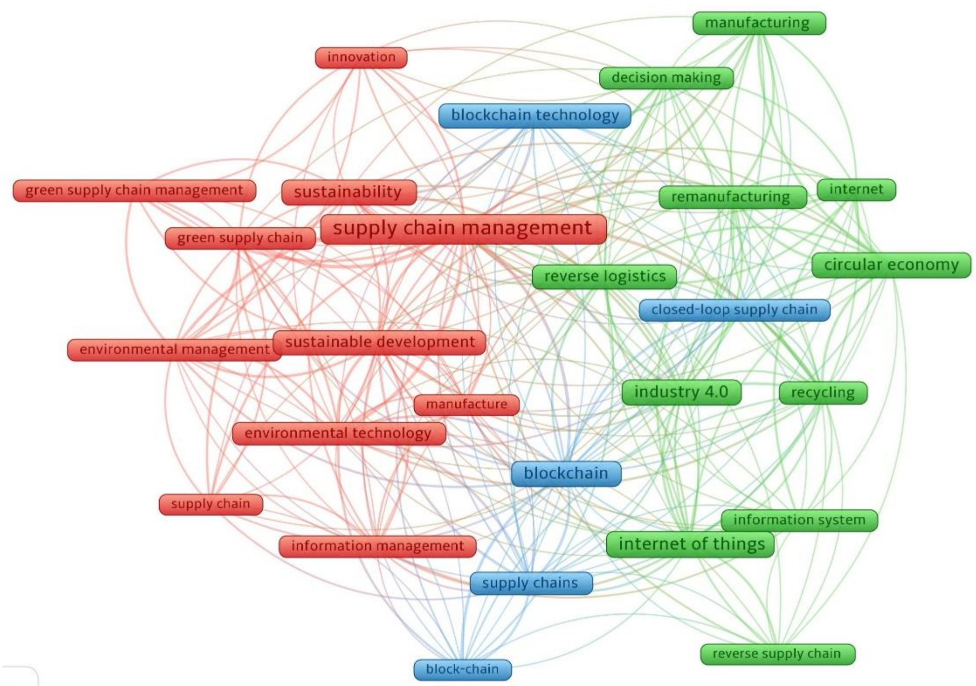

Fig. 11. Visualization of keyword sharing (created with VOSviewer)

Figure 12 shows an analysis of the common use of words with overlay visualization. With this visualization, certain periods when keywords were used in research are more visible.

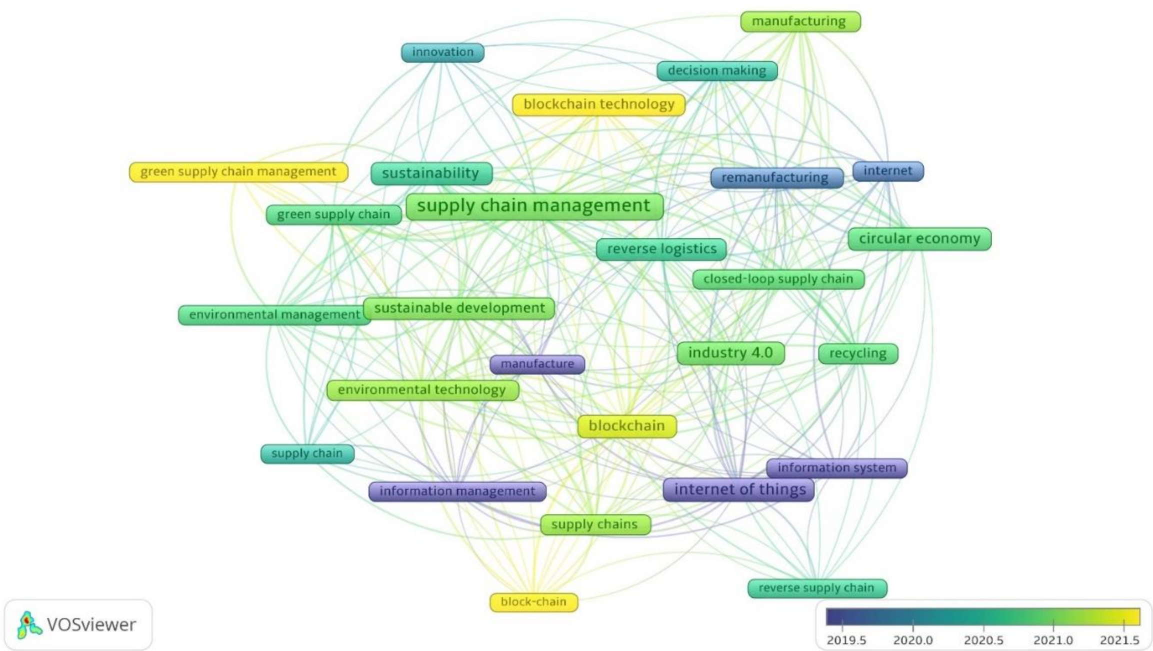

Fig. 12. Analysis of keywords by the density of their use (created using VOSviewer)

DISCUSSION

Beyond these concerns, various scholars delve into other dimensions of the digitalization of the reverse supply chain. Alcayaga et al. [2019] present a strategy employing IoT products for circular practices like reuse and recycling. Joshi and Gupta [2019] explore the IoT's potential in product recovery. Garrido-Hidalgo et al. [2020] suggest a Circular Supply Chain (CSC) framework incorporating digital technologies, including the IoT.

Camacho-Otero et al. [2018] focus on business models for waste reduction and resource reuse, exploring cultural barriers to circular economy adoption. They highlight a lack of awareness and understanding of resources and waste, which hinders acceptance. Zhang et al. [2018] address challenges in resource recovery management, suggesting the IoT as a solution to ensure timely and accurate information for real-time production planning on the shop floor.

Contemporary research addresses the impact of digitalization on remanufactured products. Alqahtani et al. [2019] highlight the IoT's role in providing accurate information about end-product components. Okorie et al. [2020] delve into the emerging field of digital recovery, focusing on recovery 4.0 or intelligent recovery. Niu et al. [2022] study consumer evaluation of remanufactured products with and without blockchain-quality information, investigating incentives for blockchain adoption by suppliers and manufacturers.

Tozanlı et al. [2020] suggest employing embedded IoT products and blockchain for efficient custom disassembly systems of high-tech industrial products, aiming at economic, environmental, and social sustainability. Trujillo-Gallego et al. [2022] employ a dynamic hierarchy of possibilities to analyze the influence of digital technologies and environmental management on environmental performance within the framework of sustainable development.

Fang et al. [2016] highlight the utilization of the Internet of Things for product life cycle data management. Subramoniam et al. [2021] delve into the digitalization of the product life cycle and its implications for product return or recovery.

Franchina et al. [2021] investigate digitalization's role in fostering environmentally friendly behavior across different economic sectors. In a similar vein, Xia et al. [2020] emphasize the significance of enabling technological innovation through innovative resources within the supply chain and the strategic selection of innovation partners in integrated supply chains.

Krstić et al. [2022b] researched the optimal scenario for an intelligent reverse logistics system to foster a sustainable circular economy and closed supply chains, involving Industry 4.0 technologies like the IoT, autonomous vehicles, and AI. Similarly, Wei et al. [2021] suggest addressing e-commerce reverse logistics challenges using IoT-driven management strategies.

Bag et al. [2021] analyze resource involvement in digitalizing procurement for enhanced enterprise productivity. Lerman et al. [2022] reveal smart supply chains' positive contribution to environmental productivity. Cheshmberah and Beheshtikia [2020] affirm digitalization's positive influence on supply chain management. Dev et al. [2021] explore stimulus investments, additive manufacturing, and supply chain sustainability for green product diffusion in Industry 4.0.

In the context of the digitalization of the reverse supply chain, interesting opportunities arise for transforming traditional processes and introducing new innovative approaches. The use of digital technologies, such as the Internet of Things (IoT), data analytics, artificial intelligence (AI), and blockchain, can accelerate and improve the efficiency of the reverse supply chain. This opens up new opportunities for sustainability, optimizing return processes, reducing waste, and improving environmental responsibility.

In addition, digital technologies facilitate the collection, analysis and processing of large amounts of data, which facilitates forecasting, the identification of trends and the improvement of decision-making in the reverse supply chain. The use of digital tools also enables greater transparency, traceability, and automation of processes, which contributes to increased efficiency and reduced costs.

In general, the digitalization of the reverse supply chain opens up new horizons for process optimization, sustainability, and service quality improvement. This is an important area that requires further research and the implementation of innovative solutions to achieve a sustainable and efficient reverse supply chain.

CONCLUSIONS

This study analyzed the digitalization of the reverse supply chain and identified various opportunities to optimize processes, support sustainability, and reduce waste. Particular attention was paid to the use of digital technologies such as the IoT, AI, and blockchain, which open up new perspectives for inventory management and improved returns processes.

However, the study did have some limitations, such as using only the Scopus database and a limited time frame. Future research in this area could analyze the impact of digitalization on the sustainability, efficiency, and environmental performance of the reverse supply chain. It is also worth exploring the challenges and opportunities associated with the introduction of blockchain technologies and advanced data analysis in this area.

In essence, the article aims to contribute to the existing body of knowledge by shedding light on the transformative potential of digital technologies in reverse supply chain management and by advocating for the adoption of innovative solutions to achieve a more sustainable and efficient reverse supply chain system.

Digital technologies can help improve the efficiency, sustainability, and environmental responsibility of reverse supply chain management, creating new opportunities to support sustainable development in this area. The results obtained can be used as a basis for further research and implementation to optimize processes and increase the efficiency of supply chain management, taking into account sustainability and environmental impact.

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ORIGINAL PAPER

LAST DECADE OF GREEN LOGISTICS WITH MULTIPLE MODES OF TRANSPORTATION: A LITERATURE REVIEW

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ABSTRACT. Background: Transportation systems with multiple modes are effective, economical, and also offer environmental benefits. This paper summarizes the contributions of multimodal and intermodal transportation systems to the progress in green logistics from 2012 to 2022. A literature survey was conducted to determine the characteristic problems in developing sustainable logistics as well as the techniques and approaches to solve them. The study identified research gaps, and the outcomes will provide a reference for researchers in future work. Published work regarding environmental issues, mode combinations, problem formulations, and solution approaches were evaluated. Research gaps were also identified, and the main requirements for future research were proposed. It was shown that intermodal and multimodal transportation problems in the field of green logistics have received substantial attention in existing literature. However, this is the first literature review of the topic that has considered the body of literature published in the last decade.
Methods: The researchers conducted a literature survey to gather relevant information on the topic, based on searching and reviewing academic papers, research articles, conference proceedings, and other publications related to multimodal and intermodal transportation systems and their impact on green logistics from 2012 to 2022. The phases of research method followed data collection, data evaluation, identification of research gaps, proposal of main requirements, and offering valuable insights for future research endeavors.
Results: The result of this study highlights the key findings, such as increasing focus on environmental consideration in multiple mode of transportation, lack of studies on uncertainty, utilizing sophisticated solution techniques, the need for different mode combinations, and integrating technological developments to the transportation systems.
Conclusions: This study shows that while there is a rich body of literature on multimodal and intermodal transportation systems, the focus has predominantly been on economic rather than environmental sustainability. Future research should prioritize environmentally sustainable multi/intermodal transportation systems, exploring multi-objective planning, integrating different vehicle types, and improving meta-heuristics to tackle real-world logistics challenges.

Keywords: Environmental impact of transportation, Multimodal transportation systems, Intermodal transportation systems, Green logistics, Comprehensive literature review

INTRODUCTION

Supply chain activities, logistics, and transportation phases all have a carbon footprint. The United States Environmental Protection Agency [EPA 2021] has reported that carbon dioxide (CO_2) emissions mainly originate from transportation, industrial, commercial, and residential sources. Awareness of environmental activities in the supply chain requires effective transportation planning within the network, and a low carbon footprint should be ensured for all operations. There is currently competition among companies over the development of sustainable logistics strategies. Environmental issues, social responsibility, and customer intentions have placed pressure on companies to increase their green logistics activities. Each mode of transport causes different carbon emissions. The carbon emission unit used by the greenhouse gas (GHG) Protocol is 0.2, 0.05, and 0.0275 for road, sea, and rail transport, respectively [GHG Protocol 2020]. Vehicle weights, road slope, and vehicle and ship speeds are ignored in the calculations for 100 km. As shown in the graphs in Figure 1, the carbon

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emissions increase linearly as the weight of the transported load increases. The mode of transport that caused the most carbon emissions was road transport, while rail transport was the most environmentally sustainable mode of transport.

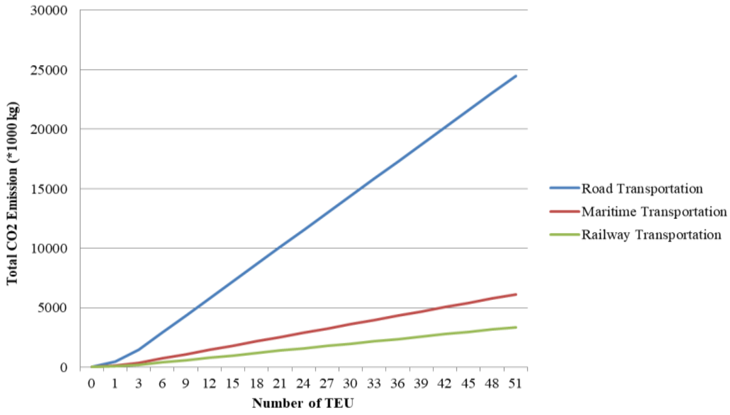

Fig. 1. CO_2 emissions of different modes of transport in freight transportation [Source: The authors].

Because of the growth in international trade and the increasing demand for international logistics, the use of more than one transportation mode has become essential for logistics service providers in intercontinental freight transportation. As shown in Figure 1, avoiding road transport in freight transportation understandably produces more sustainable solutions from the perspective of the environment, and mode combinations can generate environmentally sustainable services. According to [Sahin et al. 2014], combining road or railway transportation with a seaway is more economical over long distances than road-rail combinations. It is obvious that cost analyses considering sea-road, road-rail, sea-rail, and road-sea-rail combinations can vary based on the technical and operational parameters for different transportation systems. Researchers have discussed the modal shifts required for a greener logistics system and have listed case-by-case consequences [Eng-Larsson and Kohn 2012, Sahin et al. 2014, Islam et al. 2020, Basallo-Triana et al. 2021].

Although many literature surveys have been conducted regarding optimization problems or strategic planning for multimodal and intermodal transportation, hardly any literature surveys have investigated green concerns. This paper presents a comprehensive overview of the multimodal transportation systems in terms of environmental sustainability for the first time.

The aim of the study was to summarize the current green multimodal and intermodal transportation literature and to identify any research gaps in this field regarding published articles related to the problem from 2012 to 2022. The study approached the research from a green and sustainable logistics perspective. The following research questions were addressed to achieve the objective of this research:

1. What are the main issues that need to be examined regarding the environmental impacts of multiple modes of transportation systems?

2. How can we determine which of the mode combinations considered in existing studies of multiple modes of transportation systems has the minimal environmental impact?

3. How do researchers formulate models to study multiple modes of transportation system, and which approaches have been most widely applied to provide solutions?

4. What are the gaps in the literature that offer potential research opportunities?

The remainder of the paper is organized as follows. Section 2 describes the methodology used to conduct the study. Section 3 presents an overview of the literature. Section 4 reviews the available research to identify research gaps and future research directions, while Section 5 presents the study conclusions and summarizes the paper.

MATERIALS AND METHODS

Using the realist literature review method to identify and systematically evaluate the relevant literature, we provide a comprehensive review analysis of the available literature on green logistics with multiple modes of transportation of the last decade. Research materials are gathered by searching one or more databases and are qualitatively brought together in the review. The research was conducted in three phases. The first phase established a data collection protocol as shown in Figure 3. The second phase classified the studies that were identified, and the final phase identified gaps in the literature and recommended future research directions. First, a comprehensive search of papers was carried out with specific keywords in the ScienceDirect, Web of Science (WoS), and Scopus databases. More than ten thousand articles were found on those topics. This review focused on multiple modes of transportation systems to provide effective solutions in terms of green and environmentally sustainable freight logistics, as discussed in the introduction. Thus, the filtering criteria consisted of the following thematic keywords within the 'title': ("multimodal transportation" OR "intermodal transportation ") AND ("green multimodal transportation" OR "green intermodal transportation") AND ("sustainable multimodal transportation" OR "sustainable intermodal transportation"). The search was refined to the last decade to obtain current studies of green and sustainable multiple modes of transportation systems to obtain the latest findings from the current literature. Papers published before 2012 were therefore excluded. Many of the studies discarded were largely unrelated to the specific subject area and were limited in scope. For example, articles that focused on synchro-modal transportation and real-time fleet tracking were excluded, as were any non-peer reviewed papers. Another exclusion criterion was language, with the search protocol limited to English. Only papers categorized as (Research Area = Transportation and logistics) in academic journals were included. Our research predominantly included freight transportation rather than public transportation. Recent literature with case studies was emphasized to investigate practical examples, depending on their relevance in the research domain. Duplicated works were also excluded. As a result of this exclusion procedure, a total of 76 papers were analysed.

The aim of the filtering process was to identify research limitations and gaps in the literature in the context of green multimodal and intermodal transportation systems. For this purpose, the most relevant studies were briefly examined using a theoretical framework based on the most common characteristics, such as objectives, data collection, and solution methodologies applied to problems in the last decade.

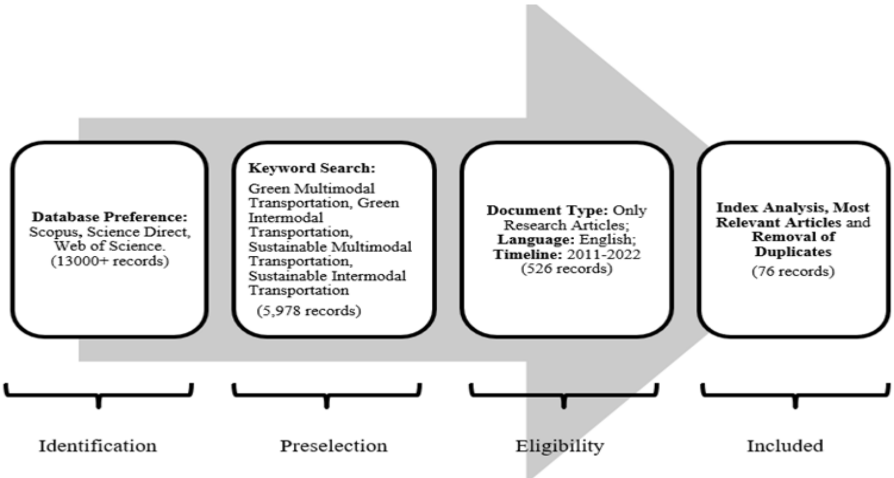

Fig. 2. Data collection protocol in this research.

RESULTS

To start our literature survey, we searched for existing literature surveys of multimodal transportation systems. We found five comprehensive literature surveys in which researchers investigated the existing literature on multimodal and intermodal transportation systems using freight planning, network design, and optimization techniques. Table 1 summarizes the scope of the previous literature and illustrates the differences with our research. [Lam and Gu 2013] addressed the future research directions for intermodal container flows in port hinterlands. [Elbert et al. 2020 and SteadieSeifi et al. 2014] identified the traditional strategic, tactical, and operational levels of planning and design required for a multimodal transportation system to ensure sustainable and reliable freight transportation. [Baykasoğlu et al. 2019] presented a structured overview of how the optimal solutions to multimodal transportation problems can be obtained. [Archetti et al. 2022] summarized the optimization techniques used in multimodal and intermodal operations as strategic/tactical and operational. A review of the effects of mode choices on environmental sustainability in freight transportation with more than one mode of transport was presented in the literature for the first time [Bask and Rajahonka 2017]. This study and ours were similar in that both examined multiple modes of freight transportation in terms of their sustainability and green logistics.

Table 1. Summary of previous literature review studies.

Reference	Type of	Scope	Timeline	N.of articles
Lam and Gu (2013)	Intermodal	Literature Review Container Flow Optimization	1972-2012	50
SteadieSeifi et al. (2014)	Multimodal	Literature Review of Freight Transportation Planning	2005-2014	78
Bask and Rajahonka (2017)	Both	The Role of Environmental Sustainability in Mode Choice	1970-2017	33
Baykasoğlu et al. (2019)	Multimodal	Literature Review of Freight Transportation Planning	1959-2017	283
Elbert et al. (2020)	Multimodal	Literature Review of Tactical Network Design	2008-2020	60
Archetti et al. (2022)	Multimodal	Literature Review of Optimization	1996-2020	111
This Study	Both	Literature Review of Multimodal and Intermodal Transportation Systems with Green Concerns	2012-2022	76

The distinguishing feature of our study was that it did not focus only on mode selection, but also provided a general perspective on environmental sustainability studies conducted during the last ten years. Although there have been many literature surveys of green or sustainable logistics and multimodal transportation systems, our study was the first literature survey to combine these subjects to consider the environmental sustainability of multimodal and intermodal transportation systems. As shown in Figure 3, environmental awareness became prominent in 2020. Although the number of such publications decreased in 2021, we noticed that publications investigating green and sustainable freight transportation in multimodal and intermodal transportation systems increased over time; however, there were fluctuations in the trend line.

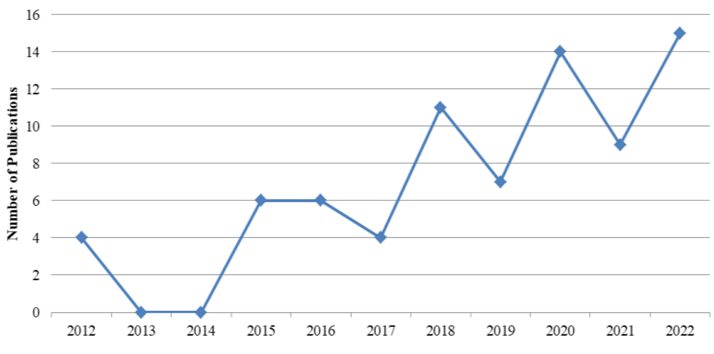

Fig. 3. Number of publications per year.

The European Commission has approved a set of policies to enable Europe's economy and society to become "climate-neutral", i.e., zero GHG emissions, by adopting step-by-step targets until 2050 [European Commission 2020]. We believe that the benefits of mode combination in freight transportation, especially after the European Green Deal is finalized, will be discussed more in the literature going forward. Figure 4 shows that Transportation Research Part E had the most publications in this area. Transportation Research Part D and Sustainability had the second-highest number of publications, with the Journal of Cleaner Production ranking third. The following part of this section examines the environmental considerations in multimodal and intermodal transportation systems, mode combinations, model formulations, and solution approaches.

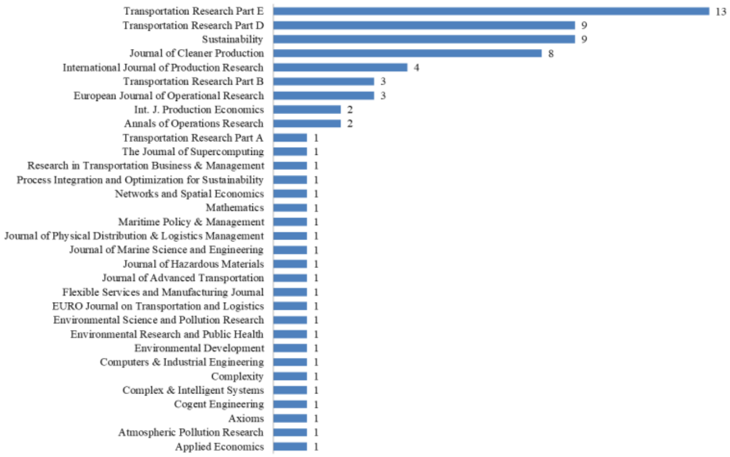

Fig. 4. Publication numbers in academic journals.

Environmental impacts of intermodal and multimodal transportation systems

To ensure greening and sustainability of the supply chain, many studies have considered minimizing the environmental impacts of logistics activities. The United Nations Framework Convention on Climate Change [UNCC 2022] has been preparing yearly Climate Action Pathways with the aim of shifting to more environmentally sustainable and low-carbon public and freight transportation modes. Removing the dependency on road transportation will play a crucial role in meeting the zero-carbon target, especially in freight transportation [European Commission 2020, EEA 2023]. To meet the decarbonization target, logistics service providers have taken action with combined transportation systems to reduce carbon emissions by a reasonable rate, compared with road transportation [MSC Shipping Company 2022, NovaTrans Greenmodal Transport Solutions 2022]. The best way to meet this target is to promote multimodal and intermodal transportation with sea and rail freight modes [EPA 2021, Rail Market News 2022].

The environmental impact of logistics activities is not limited to only GHG emissions. The other significant issues are water and air pollution, toxic waste disposal, and inefficient energy usage [OECD 2021]. However, we observed that these impacts were rarely discussed in the green logistics literature. The most reliable and efficient transportation systems need to be improved in terms of all their environmental impacts. The common environmental impacts in the existing literature were described using the terms "reducing risk", "greening concerns", and "sustainability". In the existing sustainable multimodal and intermodal transportation literature, we observed that mode choice affects sustainability when establishing green transportation. The undesired effects of road-only transportation can be eliminated by clearly switching the transportation mode throughout the system. Additionally, environmental sustainability is directly related to economic and social sustainability and vice versa. Existing studies have shown that it is possible to reduce emission rates if transportation plans include low-emission modes, compared to road-only freight transportation. There is a strong relationship between distance and carbon emissions. One likely explanation for this finding is that combinations of seaway and railway transportation are much more effective for long distance transport because of the high-volume loading capacity and lower fuel costs when trains and ships are used for freight transportation. Studies of hazmat transportation planning are common in the risk-related sustainability literature, and they play a vital role in social and environmental sustainability. For this reason, researchers have considered effective mode combinations and network design to reduce total transportation risks and the related costs.

Table 2 summarizes the general environmental impacts and gives the definitions used in the papers. As can be seen in the table, the common goal of all studies was to provide sustainability using any means of green transportation and therefore minimize the impact on the environment.

Table 2. Environmental impacts in papers.

Studies Focused on Impacts on the Environment	**References**
Green Network Design *(strategic planning that aims to reduce carbon emissions)*	Bauer et al. [2010], Bouchery and Fransoo [2015], Inghels et al. [2016], Lam and Gu [2016], Demir et al. [2016], Ji and Luo [2017], Dai et al. [2018], Jiang et al. [2020], Yang et al. [2021], Farazmand et al. [2022], Ibnoulouaf et al., [2022]
Green Routing in Transportation *(defining effectives routes by minimizing carbon emissions)*	Zhang M et al. [2015], Sun et al. [2018], Heinold and Meisel [2020], Sun [2020], Wang Q et al. [2020] Ziaei and Jabbarzadeh [2021], Choudhary et al., [2022], Qi et al. [2022]
Green Logistics *(planning eco-friendly logistics services)*	Bitzan and Keeler [2011], Eng-Larsson and Kohn [2012], Kengpol and Tuammee [2015], Kirschstein and Meisel [2015], Rudi et al. [2016], Hrušovský et al. [2018], Palmer et al. [2018], Zhao et al. [2018], Zhou et al. [2018], Demir et al. [2019], Dükkancı et al. [2019], Heinen and Mattioli [2019], Aksoy and Durmuşoğlu [2020], Li and Su [2020], Sun et al. [2021], Wang C. et al. [2020], Wang W. et al [2020], Shoukat [2022]
Sustainable Transportation *(enhancing energy-efficiency and environmental sustainability in transportation, any means of green transportation)*	Lammgard [2012], Baykasoglu and Subulan [2016], Woodburn [2017], Göçmen and Erol [2018], Resat and Türkay [2019], Martinez-Lopez et al. [2018], Kumar and Anbanandam [2020], Martinez-Lopez and Chica [2020], Ge et al. [2020], Cannas et al. [2020], Tamannaei et al. [2021], Golnar and Beškovnik [2022], Ko et al. [2022], Okyere et al. [2022]
Sustainable Network Design *(strategic planning for environmental sustainability)*	Stenius et al. [2018], Maiyar and Thakkar [2019], Tadic et al. [2019], Maiyar and Thakkar [2020], Wang et al. [2021], Mohri and Thompson [2022], Taheri and Tamannaei, [2022], Wang C et al. [2022]
Other Environmental Impact	Zanin et al. [2012], Nesheli et al. [2017], Heinold and Meisel [2018], De Miranda Pinto et al. [2018], Pizzol [2019], Zhang X et al. [2019], Wang W et al. [2020], Ardliana et al., [2022], Guo et al. [2022]
Risk *[Hazardous Materials Transportation- HazMat)*	Xie et al. [2012], Assadipour et al. [2015], Mohammadi et al. [2017], Ke [2020], Fattahi and Behnamian [2021], Li S et al. [2021]

Mode Combinations

Mode choice and mode combinations are the elements determining the greenness of the freight transportation network. Characteristics such as transit time, transportation cost, operational cost, and environmental performance vary from mode to mode. Once the size and type of transportation unit have been chosen, mode choice or mode combinations must be determined. Table 3 summarizes the different mode combinations in the literature. The road-rail combination is the most widely studied combination of transportation modes because these transportation modes are easy to combine. Connections with intermodal ports enable sea-rail intermodality to be designed. Because door-to-door deliveries are made possible by trucks, road-rail-sea combinations accurately reflect real logistics problems.

Table 3. Mode combinations in multimodal and intermodal transportation literature.

Mode Combinations	Reference	
	Multimodal Transportation Network	Intermodal Trasnportation Network
Road-Rail	Xie et al. [2012], Palmer et al. [2018], Zhang X et al. [2019], Jiang et al. [2020], Ziaei and Jabbarzadeh [2021], Farazmand et al. [2022], Ko et al. [2022]	Bitzan and Keeler [2011], Lammgard [2012], Eng-Larsson and Kohn [2012], Assadipour et al. [2015], Kirschstein and Meisel [2015], Heinold and Meisel [2018], De Miranda Pinto et al. [2018], Göçmen and Erol [2018], Sun et al. [2018], Maiyar and Thakkar [2019], Ke [2020], Sun [2020], Kumar and Anbanandam [2020], Heinold and Meisel [2020] , Cannas et al. [2020], Maiyar and Thakkar [2020], Fattahi and Behnamian [2021], Li S et al. [2021], Sun et al. [2021], Tamannaei et al. [2021], Ardliana et al., [2022], Ibnoulouaf et al. [2022], Mohri and Thompson [2022], Shoukat [2022], Taheri and Tamannaei [2022]
Road – Sea	Yang et al. [2021]	Pizzol [2019], Dong et al. [2020], Martínez-López and Chica [2020], Wang W. et al [2020]
Road – Inland Water	Inghels et al. [2016]	Wang et al. [2021]
Rail – Sea	Woodburn [2017]	Zhao et al. [2018], Aksoy and Durmuşoğlu [2020], Ge et al. [2020], Golnar and Beškovnik [2022]
Rail – Inland Water		Hrušovský et al. [2018]
Rail – Air		Zanin et al. [2012], Li Z et al. [2021]
Road – Rail – Sea	Wang C et al. [2020], Wang Q et al. [2020], Okyere et al. [2022], Qi et al. [2022]	Rudi et al. [2016], Baykasoglu and Subulan [2016], Lam and Gu [2016], Ji and Luo [2017], Resat and Türkay [2019]
Road – Rail – Inland Water	Zhang M et al. [2015], Guo et al. [2022]	Demir et al [2016], Demir et al [2019]
Road – Rail – Air	Li Z et al. [2021]	
Road – Inland Water – Sea		Dai et al. [2018]
Road – Rail – Sea – Pipeline	Wang C et al. [2022]	
Unspecified	Kengpol and Tuammee [2015), Mohammadi et al. [2017], Nesheli et al. [2017], Zhou et al. [2018], Dükkancı et al. [2019], Heinen and Mattioli [2019], Li and Su [2020]	Bouchery and Fransoo [2015], Chen and Wang [2016], Martinez-Lopez et al. [2018], Stenius et al. [2018],Tadic et al [2019]

The majority of the literature considering multimodal and intermodal transportation includes the most common mode combination of rail-road, as well as road-sea, rail-sea, and sometimes inland water transportation. However, future studies need to consider more than two transportation modes, such as road-rail-sea. Because of the model complexity, there have only been a few studies of combinations with air transport.

Model Formulations and Solution Approaches

Logistics service providers and managers have focused on reducing logistics costs because of the vital role they play in economic systems. Based on environmental impacts, many studies have developed mathematical models with green objective functions. Problems with environmental considerations have generally developed for more than one objective function, as shown in Figure 5.

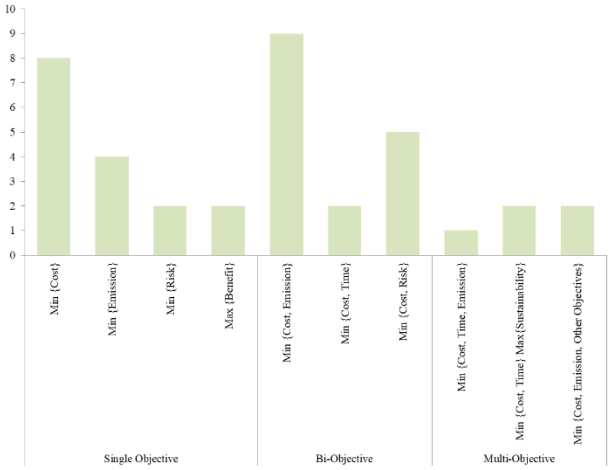

Fig. 5. Objective types.

The traditional objective function considered the economic aspects of logistics. Several studies have considered environmental effects to be a cost objective or constraint. One of the trends appearing in several studies of multi/intermodal transportation problems has been the introduction of environmental concerns as a secondary objective [e.g., Shoukat 2022, Taheri and Tamannaei 2022, Wang C. et al. 2022] to reflect applications in the real transport chain.

Multi-objective mathematical programming problems have been developed for green multimodal or intermodal transportation systems. In terms of sustainable intermodal transportation, multi-objective models with more than two objective functions have been developed to optimize the competition criteria defined by managers [Bouchery and Fransoo 2015, Baykasoğlu and Subulan 2016, Martinez-López et al. 2018, Heinold and Meiser 2020, Wang et al. 2021]. The competitiveness in terms of sustainability can be explained as improved load planning mechanisms, better service selection, and optimized intermodal routes for door-to-door transport. The objective functions can vary according to the decision-makers constrained by environmental issues [Mohri and Thompson 2022]. Table 4 details the objective structure of these modelling studies.

DISCUSSION

This section discusses some challenging issues in the available research regarding the environmental impacts of multimodal and intermodal transportation. The remaining part of this section highlights the potential research directions through the research gaps.

Research Gaps and Potential Opportunities for Future Studies

Many researchers have focused on carbon emissions; however, logistics activities also have other harmful effects on the environment. Future studies should therefore explore effective methods to handle other negative externalities, such as water, air, and noise pollution, or fuel and energy consumption.

For research question 2, the most widely studied and preferred mode combination in multimodal and intermodal transportation systems is the road–rail combination because it is more practical than the other combinations. There is a lack of research on the integration of waterways and airway transportation. The combination of three transportation modes, i.e., road, rail, and sea, is more effective as the transportation distance gets longer. The literature has not discussed air transportation with road, rail, or maritime transportation. In green transportation networks in which multiple transportation modes are used, attention needs to be given to strategic and operational problems where air transportation is included. Despite recent technological developments indicating the integration of automated and unmanned vehicles into intermodal air transportation planning [Archetti et al. 2022], there is a knowledge gap in the current literature regarding the incorporation of air transportation in combined transportation systems. Although this could theoretically provide effective solutions for decision-makers, it will also be directly applicable to real-life problems. For this reason, following and integrating technological developments into transportation systems is important. Mode synchronization and the integration of Logistics 5.0 applications require more attention for combined transportation systems. Therefore, machine learning and data mining for logistics management have become important topics in operations research.

Table 4. Objective structures by paper.

Objective Structure	Reference	Goal
Single – objective	Xie et a. [2012]	Min Total Link Risk associated with Operational Cost
	Rudi et al. [2016]	Min # of Full Truckload with GHG Emission
	Demir et al. [2016], Zhao et al. [2016], Hrušovský et al. [2018]	Min Total Weighted Cost
	Inghels et al. [2016], Ibnoulouaf et al. [2022], Okyere et al. [2022], Qi et al. [2022]	Min Total Cost associated with Environmental Cost
	Mohammadi et al. [2017]	Min Total Risk
	Zhang X et al. [2019]	Max Benefits of Railway Transportation
	Dükkancı et al. [2019], Li and Su [2020], Yang et al. [2021]	Min Total Emission
	Maiyar and Thakkar [2020]	Min Total Relative Regret
	Wang W et al. [2020], Ardliana et al. [2022], Taheri and Tamannaei [2022]	Min Total Cost
	Li Z et al. [2021]	Min Total Transportation Cost
	Mohri and Thompson [2022]	Max Government's Profit
Bi – objective	Lam and Gu [2016]	Min Total Unit Cost of Container Flow Min Total Transit Time
	Ji and Luo [2017]	Min Total Cost Min Maximum Flow Time
	Assadipour et al. [2015], Ke [2017], Li S et al. [2021]	Min Total Cost Min Risk
	Dai et al. [2018], Zhou et al. [2018], Demir et al. [20199, Maiyar and Thakkar [2019], Resat and Türkay [2019], Dong et al. [2020], Sun [2020], Wang Q et al. [2020], Farazmand et al. [2022], Shoukat [2022]	Min Total Cost Min Total Emission
	Fattahi and Behnamian [2021]	Min Total Cost Min Population Exposure
	Ziaei and Jabbarzadeh [2021]	Min Total Cost Min Total Risk with Carbon Emission
Bi – level	Zhang M et al. [2015]	Min Transhipment Cost Min Service Cost
	Jiang et al. [2020]	Max Total Flow Min Total Cost
Multi – objective	Bouchery and Fransoo [2015]	Min Total Cost Min Carbon Emission Min Modal Shift
	Baykasoğlu and Subulan [2016]	Min Total Transportation Cost Min Total Transit Time Min Total CO_2 Emission
	Ko et al. [2022]	Min Transportation Cost Min Social Cost Min environmental Cost
	Wang C et al. [2022]	Max Profit Max Energy Security Min Emission

It was also important to consider the formulation of problems and the proposed solutions in the published studies. There is an additional need for the diversification of model structures to obtain multi-objective models with different objective functions such as maximizing profit, service level, and vehicle utilization, while minimizing travel time, total distance, lead time, and environmental impact.

The number of studies based on real-life applications has grown over time, but the proposed formulations and solution techniques may be specific and inapplicable. Therefore, practical scenarios, formulations, and solutions are required to tackle real business problems. Additionally, considering the pollution routing, uncertainty in weather conditions, capacity, and emission rates some degree of scaling is required. Researchers should also focus on fleet deployment, repositioning, replacement, and sizing. These strategies will reflect real business problems if they are combined with different types of uncertainty and risk.

In addition to these knowledge gaps and future research directions, there were limitations to our study that could also provide opportunities for future research. To summarize the latest developments in green combined transportation, we considered only papers published in the last ten years (2012−2022), which obviously excluded papers published before 2012. This search excluded books, chapters, conference proceedings, and articles that were not in English, but they may still be relevant studies. Considering the review's findings on the trends and research gaps in the available literature, answers can be provided to the initial research questions; however, additional information may also be available. This study collected data from the aforementioned databases using criteria established to ensure the quality of the content. This might have resulted in some data loss due to the exclusion of studies not indexed in the databases.

Most of the available studies focused on network design rather than routing problems. Regarding research question 3, the findings indicated that routing decisions or fleet planning models should be explored. Most of the approaches taken in the studies reviewed focused on multi-objective optimization techniques. However, the proposed formulations and solution techniques were often specific and inapplicable. For real-world applications, more sophisticated methods, such as practical scenarios, formulations, and solution techniques that can tackle real business problems need to be developed. This would enable research question 4 to be fully answered.

We observed that researchers have mainly focused on time uncertainty in transportation planning (i.e., transit, arrival, or departure times). Most of the reviewed studies published in the last five years showed an increasing interest in studying uncertainty in multimodal transportation systems. Only a few studies have considered uncertainty in demand, capacity, and risk. We also noticed that studies considering uncertainty have proposed fuzzy, stochastic, or robust optimization techniques according to the problem structure. Researchers have generally developed the chance-constraint method and sample average approximation (SAA) in addition to metaheuristics in stochastic cases, while some authors have developed fuzzy optimization techniques in fuzzy cases. Simulations, fuzzy optimization, and robust optimization techniques are generally used to handle uncertainty parameters.

Furthermore, it is necessary to use metaheuristics to solve operational decisions such as location, routing, and scheduling problems, which are NP-hard problems, especially at large scales and in a reasonable time. Figure 6 shows the solution methods presented in the reviewed literature. Because the complexity of the problem increases for large-scale real-life transportation problems, the development of sophisticated solution methodologies is required.

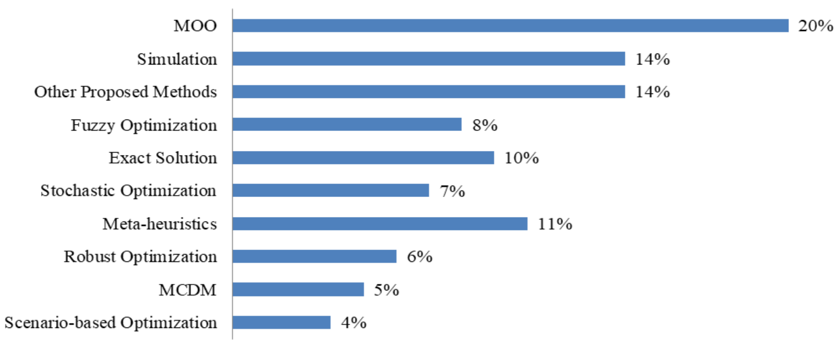

Fig. 6. Solution methods.

We conclude that there is a need for a massive computational effort due to the complexity of the problem. Combined transportation system planning problems are classified as NP-hard problems. Due to the natural consequences of problem complexity, metaheuristics, and hybrid heuristics, they are often proposed in studies for especially large-scale problems.

CONCLUSIVE REMARKS

Capturing and interpreting the trade-offs among economic, environmental, and social consequences is critical for designing and managing an efficient transportation system. Thus, researchers, policy-makers, and practitioners have paid increasing attention to the environmental advantages of transportation systems with multiple-transportation modes. In this paper, we reviewed the proposed multiple modes of transportation systems with a focus on their environmental impacts. There is a rich body of literature reviewing multimodal and intermodal transportation systems because researchers have typically paid more attention to economic than environmental sustainability. There is a need for review studies focusing on environmentally sustainable multimodal or intermodal transportation systems. We also focused on the research gaps to develop a theoretical framework for future green multimodal and intermodal transportation systems. Our study revealed that researchers and practitioners are willing to consider environmental sustainability goals because transportation activities are the leading GHG emitter. To address the research gaps summarized above, future studies should consider multi-objective transportation planning that combines different vehicle types, such as integrating air transportation with the combination of road and seaway transportation. The various uncertain parameters should also be resolved by improving meta-heuristics for large-scale real-case logistics problems. Developing technologies in the logistics sector with new strategies regarding environmental concerns in logistics is another interesting research direction for future studies.

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