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Resilience strategies for risk environments in the foreign trade logistics operations of SMEs

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Keywords: resilience, risks, principal component analysis, flow logistic, supply chain.
Abstract: Foreign trade fosters a country's economic growth and ensures that consumers can satisfy their needs and that SMEs can compete in other markets, both domestic and international. International negotiations require multiple strategic decisions between buyer and seller, such as the location of the supplier of inputs or raw materials, price, quality, management of information, the contracting of logistics operators, the terms of international negotiation, and in addition, compliance with international regulations and the legalization of the goods established in trade agreements or free trade agreements between countries. However, multiple internal and external variables in foreign trade logistics processes jeopardize the optimal flow of the chain. In consideration, SMEs are more affected. This research, in addition to identifying and studying, through principal component analysis, the different variables that pose a risk of disruption in the foreign trade logistics operations of SMEs, allows for the alignment of strategic decisions to minimize risk and increase the resilience of SMEs. It should be noted that, in the study, a 26-question survey was designed and applied to a sample of 63 Colombian SMEs, and SPSS version 25 software was used.

1   Introduction

In recent years, organizations have faced multiple external conditions, most recently the SARS-CoV-2 pandemic, which has jeopardized their permanence in the markets. However, the immense complexity of supply chain structures makes them vulnerable to risks and, consequently, to disruptions. It is important to mention that risk always exists, but the capacity to respond must be developed based on resilience strategies. In order to mitigate risks in foreign trade operations, information technologies should be used so that there is fast and timely communication between intermediaries in a chain, and also to facilitate real-time risk monitoring, so that actors identify and respond to risks collaboratively; this will allow agility and adaptation to different situations, such as supplier delays or political instability in one or more countries.

It should be noted that, through free trade agreements, companies can control the costs of international trade, have access to more suppliers located in different countries and enjoy benefits in the payment of tariffs or taxes for the legalization of cargo coming from countries with trade agreements [1]. In this sense, it is necessary to properly control the activities of mobilizing goods from one place to another and properly manage costs [2]. A country's logistics costs feed the logistics performance indexes established by the World Bank, which directly affects the competitiveness and confidence index. It is worth mentioning that foreign trade generates economic stability for the trade balance of countries [3]. Hence, the World Bank measures the logistics performance of countries through different indicators, all focused on international trade.

Due to their size, preparedness, and responsiveness, SMEs are the most vulnerable to the risks of foreign trade operations. In a changing world, risks exist in macro and micro contexts due to the very political, social, and economic nature of each country, which creates instability in international business, international currency fluctuations, and uncertainty between supply and demand, all of which directly affect the final price of the product. Therefore, it is necessary to prepare SMEs to design resilience strategies and venture into international markets. Resilience is the willingness to identify, accommodate, and absorb fluctuations, disturbances, disruptions, and surprises [4].

The objective of the paper is to identify the risks in the foreign trade operations of SMEs based on an exhaustive bibliographic review. Subsequently, to group the risks (variables) identified, a survey was designed with closed questions

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and response options on a Likert scale. The survey was sent to 100 employees of SMEs in charge of foreign trade, international business, supply chain, and internationalization operations, and 63 of them responded. It should be noted that the information collected through the surveys is statistically reliable. For this purpose, Cronbach's Alpha was used, and to group the risks by affinity, principal component analysis was applied, which resulted in resilience strategies for risk environments in the foreign trade logistics operations of SMEs.

2   Literature review

A supply chain is a set of actors that mobilize goods and services from the origin of raw materials to the final consumer. This involves integrating human and monetary resources, which brings privileges to the parties involved. However, supply chains are also exposed to various risks, such as delays [5], failures [6] and disruptions [7], demand and supply uncertainty, changes in cost rates, quality issues, business performance [8] and price fluctuation [9].

Risk management in the supply chain allows to typify them, analyze them and make decisions to control them [10] but also improves the flexibility and agility of actors [11], the traceability of operations [12] and the efficient flow of information [13], which reduces the impact of risks. Risks are events with negative or positive effects on people and organizations, so it is necessary to correct them, maintain them, and propose continuous improvements in risk management. The goal is to strengthen the structure of the supply chain to combat risks and uncertainties [14]. On the other hand, risk management requires the involvement of the customer, marketing, operations, technology, and customer service [15], as these actors are interrelated to enable the efficient flow of goods, services, and information [16].

Most SMEs have complications in international negotiation processes, especially in finance. Therefore, these firms need intermediaries in foreign trade operations that provide value between buyers and sellers [17], generate knowledge, manage risks, and develop effective resilience strategies to stay in markets [18]. On the other hand, cumbersome paperwork or the centralization and bureaucracy of some countries in the international environment can cause cost overruns and affect international trade [19]. Risk management enhances business competitiveness based on four fundamental principles: identifying, assessing, mitigating, and controlling risks [20]. However, strategy development begins when organizations assimilate the impact of risk [21].

SMEs with foreign trade operations must be prepared to deal with internal and external crises, provide effective, timely, and rapid response to strategic supply chain partners, measure recovery time in the face of atypical situations, and have the ability to share risks with different intermediaries [22]. However, all this requires professional human capital with experience, attitude, and risk perception. It is important to note that man-made events create a domino effect in the supply chain, require the most effort and dedication, and take longer to recover from [23].

According to [24], six supply chain risks are identified: supply risk, process risk, demand risk, logistics risk, collaboration risk, and environmental risk. In turn, [25] identify four risks: supply risk, financial risk, information risk, and manufacturing risk. This leads to the identification of risk environments in this research. It should be noted that the study was conducted in Colombian SMEs, which are classified according to the number of employees and their level of annual turnover, according to Decree 957 of 2019 [26], and according to their participation in the GDP, with a contribution of 35% and 65% of employment [27].

3   Methodology

This research begins with the identification of risk environments and continues with the design of a survey to analyze and identify the risks of these environments. The information obtained from the survey is statistically validated. On the other hand, Principal Component Analysis (PCA) is applied to group the risks by environment and, in this way, design resilience strategies for risk environments in foreign trade logistics operations for SMEs (Figure 1).
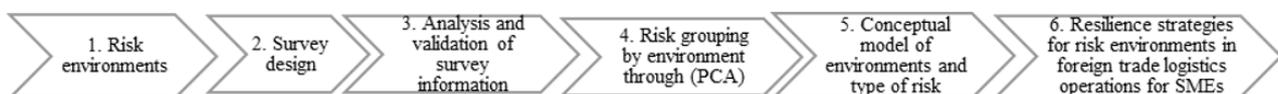
Figure 1 Research methodology
Source: Own elaboration (2024)

3.1   Risk enviroments

From a comprehensive review of the literature, the four environments that generate different risks (Figure 2) in the foreign trade logistics operations of SMEs were identified: the political environment, the economic environment, the social environment, and the legal environment.

Each risk is associated with different environments involved in the movement of goods from origin to destination, specifically in the logistics process of international trade.

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3.2   Survey design

A survey was designed and applied to SMEs that carry out foreign trade operations in Medellín (Colombia) to identify the risks of each environment. The sampling was done by convenience and the result is a sample of 63 SMEs that had to meet two main requirements. First, they had to be classified as small or medium-sized companies based on the number of employees or turnover. The second requirement is that these companies have carried out foreign trade operations in one of the business internationalization strategies [28].

The survey consists of 26 questions with response options on a Likert scale of 5 to 1, where 5 is "very important," 4 is "important," 3 is "not very important," 2 is "somewhat important," and 1 is "not at all important. The questions are divided into four sections, each focusing on a different environment (Figure 1). This survey was sent to foreign trade professionals and SME managers. The data were collected between February and April 2024 and analyzed using SPSS statistical software, version 25 for Windows.
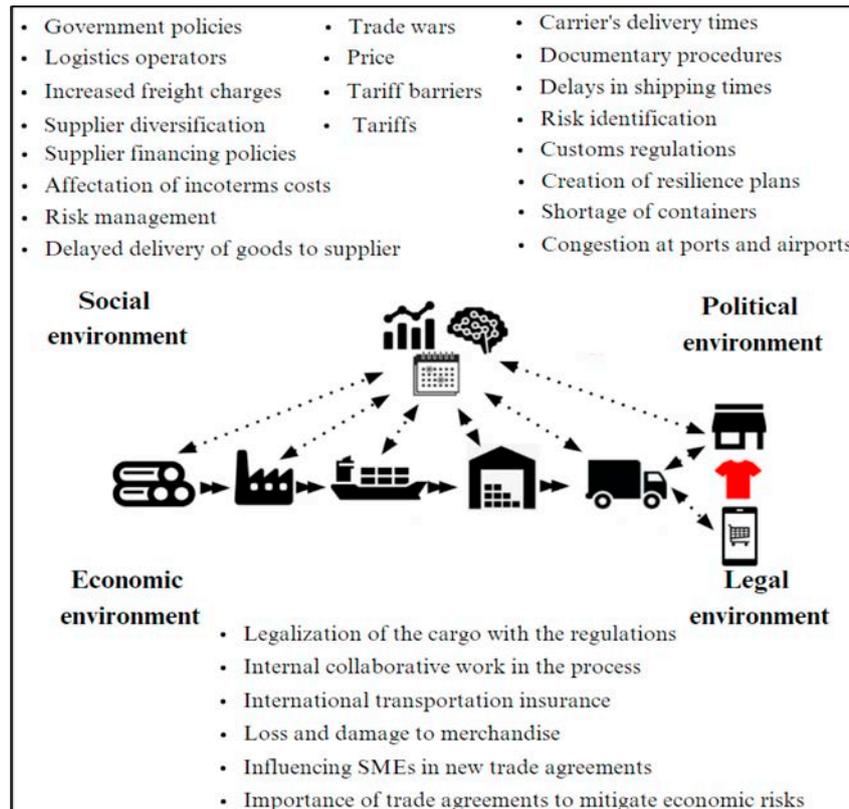
Figure 2 Risk environments
Source: Own elaboration (2024)

3.3   Analysis and validation of survey information

The reliability of the survey is validated by Cronbach's alpha, where a value below 0.70 is considered low and unreliable, from 0.70 to 0.80 reliable, and above 0.80 very reliable [29]. According to the above criteria, the survey is considered reliable, with a reliability index of 0.863 (Table 1).

Table 1 Reliability statistics

Cronbach's alpha	N of elements
0.863	26

3.4   Principal Component Analysis (PCA)

Statistical models interpret the correlation that may exist between a group of variables that must be classified by affinity into components (risk environments) [30]. In this research, principal component analysis has been applied, which makes it possible to use most of the information obtained from the data and to identify the correlation between variables. In addition, it identifies the variables that explain the most significant proportion of the total variance. The result of this statistical technique is the regrouping of the variables into factors.

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Before performing the principal components analysis, it is necessary to perform the Kaiser-Meyer-Olkin (KMO) statistical measure to determine whether the data are suitable for factor analysis. This statistic is distributed in values between 0 and 1, and the higher the value, the more related the variables are to each other. It recommends not accepting a factorial model if the KMO is less than 0.5; between 0.5 and 0.7, the quality of the sample is mediocre; between 0.7 and 0.8, the quality is good; between 0.8 and 0.9, the quality is very good; and above 0.9, it is excellent [31]. Bartlett's sphericity test analyzes whether or not the variables are correlated. If the value of the null hypothesis is zero, there is a correlation; that is, the correlation matrix is identity. This statistic is asymptotically distributed according to a chi-squared distribution with $(p-1)/2$ degrees of freedom; high values of the statistic associated with small significance values allow us to reject the null hypothesis and conclude that the variables in the sample are sufficiently correlated with each other to perform factor analysis. If Bartlett's test of sphericity does not allow the null hypothesis to be rejected, the factors in which the original variables are included could be calculated, although these would be wholly spurious and would not correspond to the correlations that exist between the variables; to conclude that there is a correlation between variables, the value of the correlation matrix must be zero [32].

In this study, the KMO value is 0.788; therefore, the data matrix is appropriate for applying principal component analysis and is further confirmed by the significance associated with Bartlett's sphericity test, which is 0.000 (Table 2).

Table 2 KMO and Bartlett's test

Statistic		Value
Kaiser-Meyer-Olkin measure of sampling adequacy		0.788
Bartlett's sphericity test	Approx. chi-squared	870.950
	gl	325
	Sig.	0.000

The objective of Principal Component Analysis (PCA) is to reduce the dimensionality of the data. When evaluating the proportion of the accumulated variance explained, the minimum number of components is selected, after which the increase is no longer significant. Table 3 shows that 7 components have a total value greater than 1 and explain 69.14% of the total variance.

Table 3 Total variance explained

Component	Initial eigenvalues			Sums of squared extraction loadings			Sums of squared sortation loadings		
	Total	% variance	% cumulative	Total	% de variance	% cumulative	Total	% de variance	% cumulative
1	8.263	31.782	31.782	8.263	31.782	31.782	7.214	27.746	27.746
2	2.803	10.782	42.564	2.803	10.782	42.564	2.170	8.345	36.092
3	1.884	7.244	49.808	1.884	7.244	49.808	1.982	7.623	43.715
4	1.456	5.601	55.410	1.456	5.601	55.410	1.846	7.100	50.815
5	1.332	5.124	60.534	1.332	5.124	60.534	1.790	6.883	57.697
6	1.161	4.464	64.997	1.161	4.464	64.997	1.489	5.728	63.425
7	1.077	4.144	69.141	1.077	4.144	69.141	1.486	5.716	69.141
8	0.937	3.606	72.747						
9	0.862	3.317	76.064						
10	0.801	3.082	79.146						
11	0.743	2.856	82.002						
12	0.619	2.382	84.384						
13	0.595	2.290	86.674						
14	0.555	2.133	88.807						
15	0.428	1.648	90.455						
16	0.418	1.606	92.061						
17	0.363	1.396	93.457						
18	0.312	1.199	94.656						
19	0.276	1.060	95.716						
20	0.259	0.995	96.711						
21	0.227	0.871	97.582						
22	0.191	0.734	98.316						
23	0.182	0.699	99.016						
24	0.120	0.461	99.477						
25	0.083	0.318	99.795						
26	0.053	0.205	100.000						

Extraction method: Principal Component Analysis

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Table 4 shows the rotated component matrix obtained using the varimax rotation method, which converges to 7 interactions. It should be noted that this method groups the variables into different components and that each variable is grouped into the component where the correlation is significant.

Table 4 Rotated component matrix

	Component						
	1	2	3	4	5	6	7
1. Logistics operators	-0.048	0.302	-0.252	-0.093	0.666	0.232	-0.075
2. Supplier diversification	0.077	0.346	-0.235	0.636	-0.212	0.273	-0.068
3. Supplier financing policies	-0.035	0.117	0.051	-0.059	-0.062	0.142	0.791
4. Risk identification	0.278	0.703	0.283	0.057	-0.044	-0.004	-0.037
5. Creation of resilience plans	0.270	0.149	0.763	0.170	0.022	0.022	0.077
6. Influencing SMEs in new trade agreements	0.059	0.111	0.203	0.160	0.322	-0.260	0.588
7. Tariff barriers	-0.006	0.177	0.140	0.727	0.042	-0.057	0.119
8. Importance of trade agreements to mitigate economic risks	0.091	-0.080	0.194	0.823	0.187	-0.119	-0.065
9. Internal collaborative work in the process	0.135	0.654	0.298	0.078	0.205	0.154	0.291
10. Customs regulations	0.215	0.327	0.733	0.067	0.017	0.128	0.171
11. Legalization of the cargo with the regulations	0.059	0.789	0.014	0.143	0.030	-0.081	0.094
12. Loss and damage to merchandise	0.796	0.024	0.074	0.093	-0.116	0.026	0.120
13. Delayed delivery of goods to supplier	0.760	0.219	-0.288	0.044	0.074	-0.038	0.120
14. Increased freight charges	0.828	0.123	0.021	0.082	-0.121	-0.171	0.052
15. Documentary procedures	0.757	0.029	0.378	0.102	-0.107	0.070	-0.122
16. Trade wars	0.568	0.061	0.130	-0.077	0.436	0.124	0.140
17. Shortage of containers	0.703	0.008	0.210	0.087	0.129	0.113	-0.089
18. Congestion at ports and airports	0.843	0.181	0.150	-0.108	0.097	-0.141	-0.142
19. Delays in shipping times	0.824	0.076	0.141	-0.068	0.145	-0.186	-0.248
20. Carrier's delivery times	0.803	0.184	0.169	0.031	0.180	-0.156	-0.214
21. Tariffs	0.724	0.070	0.160	0.059	0.075	-0.057	0.121
22. Government policies	0.697	0.018	0.081	0.044	0.338	0.173	0.214
23. Risk management	0.186	0.236	0.242	0.136	0.305	0.578	0.242
24. Affectation of incoterms costs	0.209	-0.117	0.134	0.202	0.756	0.068	0.083
25. International transportation insurance	-0.138	-0.078	0.030	-0.099	0.110	0.785	-0.044
26. Price	0.736	-0.009	-0.014	0.035	0.012	0.278	0.161

Extraction method: Principal Component Analysis
Rotation method: Varimax with Kaiser normalization

A reliability analysis was also applied with the split-half method, in which the total variables are divided into two halves. The result for part 1 has a Cronbach's alpha of 0.68, while part 2 has 0.87, which is considered acceptable for both parts (Table 5).

Table 5 Split-half method

Reliability statistics			
Cronbach's Alpha	Part 1	Value	0.681
		N of element	13[a]
	Part 2	Value	0.879
		N of element	13[b]
	N total number of elements		26
Correlation between forms			0.502
Spearman-Brown Coefficient	Equal length		0.669
	Unequal length		0.669
Guttman two-half coefficient			0.644

a. The variables are: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13.
b. The variables are: 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26.

Split-half method obtained from SPSS

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Finally, the variables are then grouped in the component (risk environment), where they have a significant correlation. In this research, seven components were obtained, which are strategically named according to the affinity of the variables, and which group the 26 variables (Figure 3).

4   Results and discussion

Conceptual model of risk environments in foreign trade logistics operations for SMEs. Based on the results of the PCA, the conceptual model of risk environments in foreign trade logistics operations for SMEs is obtained. This model is represented by seven risk environments of foreign trade operations in SMEs, each environment grouping several variables (Figure 3).
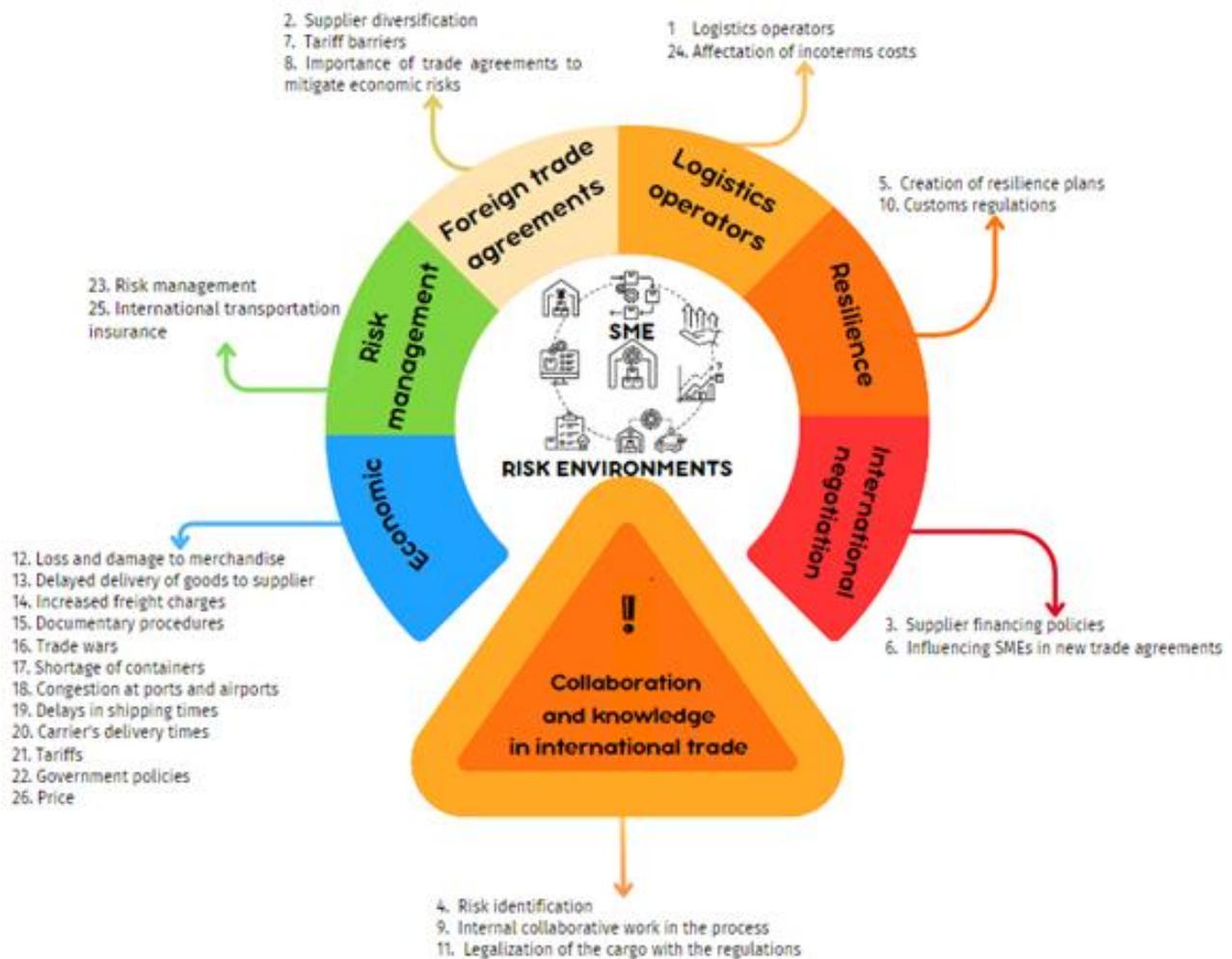
Figure 3 Conceptual model of risk environments in foreign trade logistics operations for SMEs
Source: Own elaboration (2024)

Robustness is defined as proactivity, while they understand flexibility and agility as reactivity. robustness as the ability to withstand and respond to an impact, which implies defining resilience strategies as the normalization of operations after a disruption [33].

Resilience strategies for SMEs with foreign trade operations must be unified not only with planning and execution but also with knowledge, flexibility, strategic allies, negotiations, and political, economic, social, technological, environmental, and legal uncertainties. The results obtained in this research allow designing resilience strategies oriented to the selection and evaluation of raw material and input suppliers (a), selection and evaluation of logistics operators (b), information systems and collaborative communication (c), organizational structure (d) and human capital expert in foreign trade operations (e). These resilience strategies will have an impact on the different risk environments (Figure 4), which will allow SMEs with foreign trade operations to be robust and flexible in order to increase their capacity for agility and adaptability.

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SPECIFIC RESILIENCE STRATEGIES

RISK ENVIRONMENTS	✓ Selecting and evaluating raw material and input suppliers	✓ Selection and evaluation of logistics operators	✓ Professional human capital in international trade
Economic	13. Delayed delivery of goods to supplier 26. Price	12. Loss and damage to merchandise 14. Increased freight charges 17. Shortage of containers 18. Congestion at ports and airports 19. Delays in shipping times 20. Carrier's delivery times	15. Documentary procedures 16. Trade wars 21. Tariffs 22. Government policies
Risk management			23. Risk management 25. International transportation insurance
Foreign trade agreements	2. Supplier diversification		7. Tariff barriers 8. Importance of trade agreements to mitigate economic risks
Logistics operators		1. Logistics operators	24. Affectation of incoterms costs
Resilience			5. Creation of resilience plans 10. Customs regulations
International negotiation	3. Supplier financing policies		3. Supplier financing policies 6. Influencing SMEs in new trade agreements
Collaboration and knowledge in international trade			4. Risk identification 9. Internal collaborative work in the process 11. Legalization of the cargo with the regulations

✓ Organizational structure

✓ Collaborative information and communication systems

TRANSVERSAL RESILIENCE STRATEGIES

Figure 4 Resilience strategies for SMEs with foreign trade operations
Source: Own elaboration (2024)

The objective of the strategy for selecting and evaluating suppliers of raw materials and inputs is to select reliable suppliers that offer good value for money, with whom a solid business relationship can be established that reduces both prices and uncertainty between supply and demand. Suppliers that can adapt to changing needs and provide accurate and timely deliveries will help improve customer service levels and competitive positioning. In addition, an advantage should be gained from suppliers located in other countries with which there is a trade agreement or free trade agreement in force. On the other hand, it is important to emphasize that the evaluation and selection of suppliers are essential processes to prevent risks related to third parties.

A logistics network is a system that must efficiently connect production and consumption activities (sales to the end customer). Its main objective is transportation and warehousing, and although it seems simple, it is a complex planning that requires a large number of resources. For this reason, it is better to outsource it through logistics operators (OPL) since many variables must be considered, such as procurement policy, volume of goods, transportation systems, available warehouses, racking configuration, and forecasts, among others. In this sense, the selection and evaluation strategy of the OPL must be based on the evaluation of transportation costs, the level of customer service, and the fulfilment of delivery promises.

The strategy of professional human capital in international trade is essential for decision-making in various scenarios of foreign trade operations. Professionals must have specialized knowledge of trade agreements, customs regulations, and tariff barriers established by the World Trade Organization. It is necessary to have a broad understanding of the laws related to the import of goods into the country since the related guidelines are very dynamic and affect the flow of goods, causing significant delays and customs expenses. On the other hand, it is much more beneficial to know the incentive programs that a government creates to reduce taxes for exporting companies. The field of international trade is a crucial point, so the selection and maximization of each human resource is the most critical factor to being successful at the

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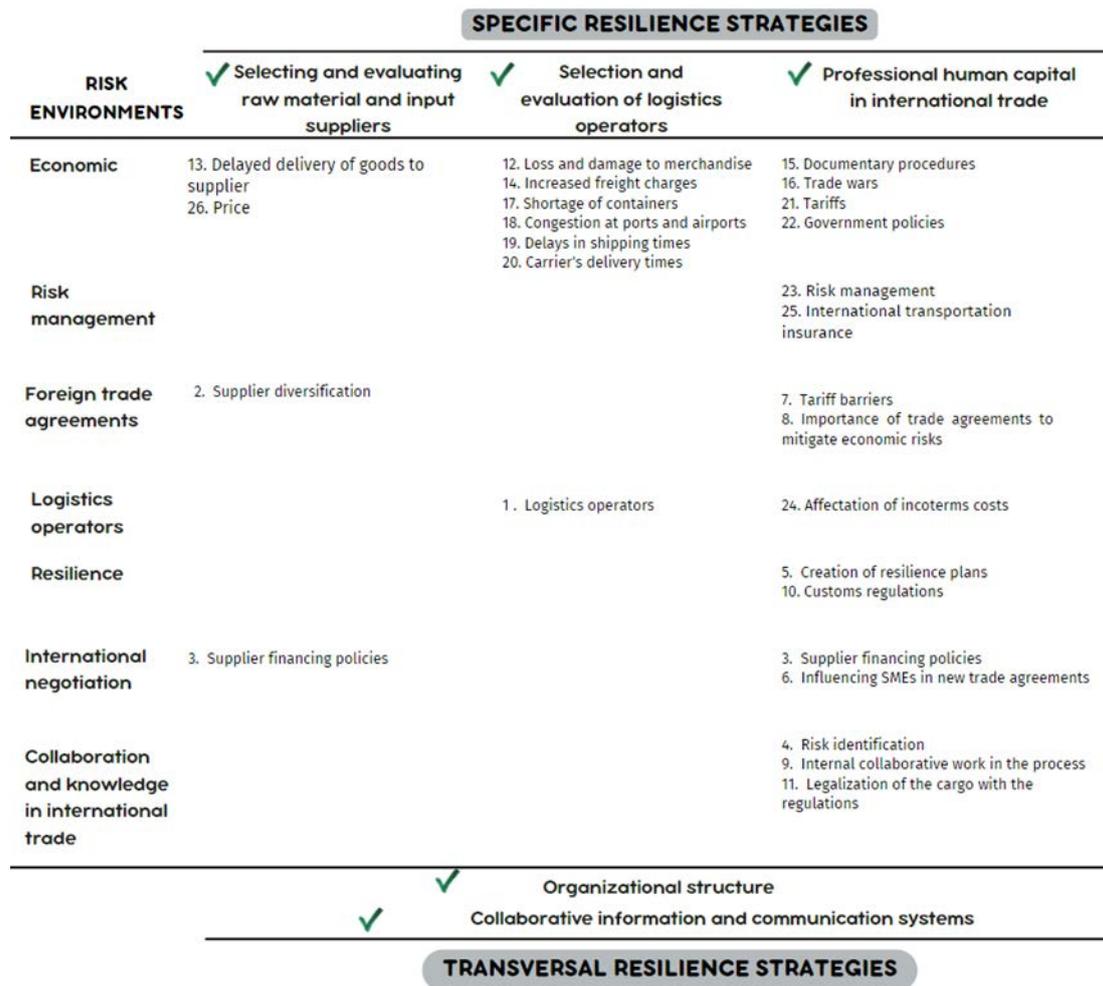
organizational level. It should be noted that the professionalization and experience of human capital also allow the creation of resilience plans.

In the competitive business world, SMEs face a number of challenges to achieve success. However, organizational structure is crucial yet constantly overlooked. The relationship between a well-defined organizational structure and the success of an SME is profound and multifaceted. A well-designed organizational structure strategy should clearly distribute the roles and responsibilities of each member of the company to create effective communication channels, enable quick and efficient decision-making, and avoid duplication of tasks. On the other hand, the organizational structure allows flexibility and adaptability to market changes and new opportunities. Flexibility facilitates innovation, as ideas flow without too many bureaucratic obstacles. It also fosters employee motivation and commitment by providing a clear and organized work environment that improves productivity, which is essential for sustainable growth.

The strategy of collaborative information and communication systems (internal and external) enables agile management in the review of documentation by all stakeholders and compliance with regulatory and legal processes. It offers greater traceability of operations throughout a supply chain. It should be noted that technological tools are necessary to identify, quantify, and mitigate risks [34]. Companies will have greater visibility to act faster on risks. In this sense, the risks inherent in foreign trade logistics operations can be minimized through three specific strategies and two cross-cutting strategies, which increase responsiveness and flexibility (Figure 5).
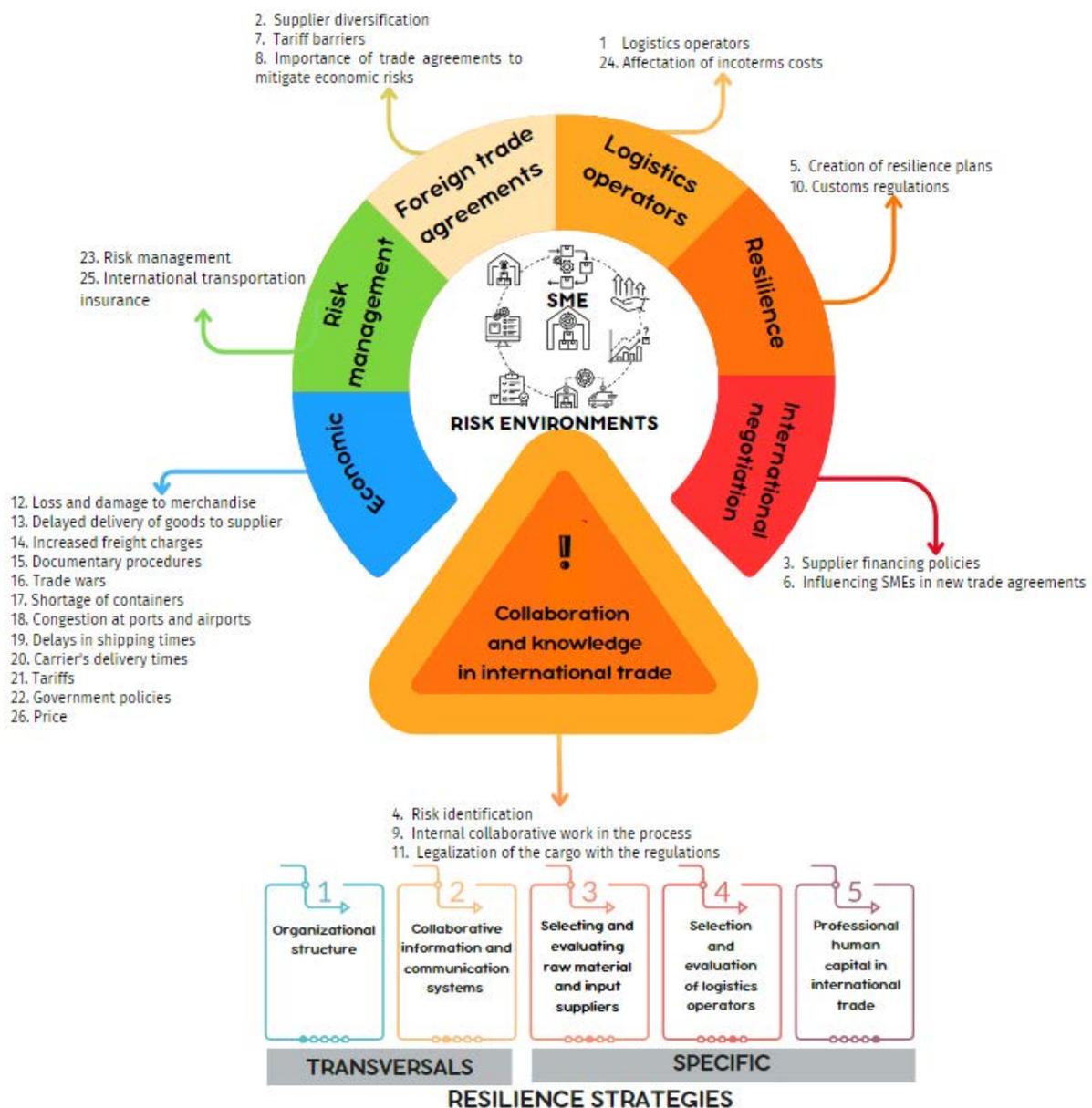

Figure 5 Resilience strategies for risk environments in the foreign trade logistics operations of SMEs
Source: Own elaboration (2024)

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5   Conclusions

Among the findings of research, that economic risk is the most important for SMEs. However, they also mention some sub-criteria with a high level of importance, such as work environment, human error, and supplier quality. These findings show that the economic environment is the one with the highest number of risks (12 variables). In addition, the environment of collaboration and knowledge of SMEs in international trade processes is essential within SMEs. The educational profile or training of personnel in areas such as supply chain and logistics operations within an organization is closely related to the attitude to detect and perceive risk; this implies that it is necessary to have qualified personnel with knowledge of foreign trade and international regulations, with adequate preparation and experience. This requires an exchange between educational institutions and SMEs.

SMEs have limited financial capacity, which prevents them from implementing resilience strategies beyond their means. However, in the medium and long term, they should include in their projections technological tools that support the information overload along a supply chain for their strategies, such as data mining, artificial intelligence, and blockchain in logistics, the implementation of resilience indicators and thus be able to improve decision making and increase their level of competitiveness in international trade, without losing sight of the fact that technological development can attract new risks, such as computer or cyber risk. The correlation of the supply chain with technological tools enables a compact base in the short, medium and long term for organizations to be more resilient [35]. The technology called blockchain is essential for the analysis and minimization of risks in the different logistics services in a company.

In this research, information has been obtained on SMEs, which play a significant role in the world economy. However, it is essential to clarify that SMEs have low cash flow and few assets. This situation does not occur in large companies, whose cash flow is significant and whose assets have increased dramatically in value, which helps to mitigate the impact of risks and may spark future research to compare the risks of SMEs and large companies. This research may have a second stage where we can include a factor with environmental, technological, sustainability, and sustainability risks for SMEs and identify the impact of climate change on supply chain performance.

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Fiscal and regulatory incentives for electric vehicle adoption in Polish micro-enterprises: economic analysis and policy recommendations

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Abstract: Microenterprises constitute the dominant group of companies in Poland, but rarely adopt electric vehicles (BEVs) due to high purchase costs, limited range, underdeveloped charging infrastructure, and the typical short-term investment horizons of microenterprises. This study aims to analyze microenterprises' opinions on BEVs in Malopolskie voivodship and to evaluate the effectiveness of incentives. A CAWI survey of 307 respondents (90% confidence, 10% margin of error) tested the hypothesis that BEVs would become more popular among microenterprises if there were more incentives for their purchase (even though according to respondents, BEVs are suited to city-center access (where combustion engines are banned) or serve as second cars for long trips, given their lower versatility and longer charging times). Results of the survey show that 84.4% of journeys are below 300 km (BEV range), but 65-78% of respondents provide the following barriers to BEV adoption: high price, range anxiety, insufficient charging stations, and long charging times. According to the survey, the following are significant incentives to buy BEVs: subsidies up to PLN 40,000 (8.5%), free city parking, and free city access to low-emission zones. The survey also showed that 20.5% of respondents planned to buy passenger BEVs, and 7.5% planned to buy delivery BEVs.

1   Introduction

Global pressure to decarbonise and the requirements of the EU Green Deal have forced companies worldwide to incorporate sustainable transport into their operations, particularly through the use of battery-electric vehicles (BEVs) to reduce emissions and achieve net-zero targets. Micro-enterprises (MEs), which form the backbone of emerging economies, play a key role in this transition by driving the diffusion of local innovation, job creation, and poverty reduction. These entities stimulate technology adoption, capital mobilisation, and local entrepreneurship in global value chains. In Poland, micro-enterprises dominate, accounting for 97-98% of all businesses and generating around 30% of GDP, yet despite legal requirements and subsidies, their vehicle fleets are predominantly powered by combustion engines.

Micro-enterprises differ significantly from larger companies: they are owner-managed, undercapitalised, informally managed, unstable, and have limited productivity, often operating outside formal institutions but within informal ones. They prefer versatile, easy-to-maintain compact cars or vans that support logistics flows, particularly the management of materials for deliveries, human flows during customer visits, and information flows during business trips, prioritising manoeuvrability and cost-effectiveness. However, despite the operational need for vehicles, the implementation of electric vehicles among Polish micro-enterprises remains negligible – well below 1% in small businesses [1]. This delay persists despite the introduction of low-emission zones by the EU and programmes such as NaszEauto (subsidies of up to PLN 40,000 for leasing).

In the discussion on electric cars, three main barriers to their use are mainly pointed out, namely: high initial costs, range limitations and access to charging [1]. No one seems to deny the high initial costs of owning a BEV. However, opinions on the total cost of ownership (TCO) are ambiguous: some authors argue that the TCO of electric cars is lower

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than that of combustion engine cars [2], while others claim that this is only true under particular conditions (high subsidies, entry bans, specific climate [3,4], while still others argue that the TCO of electric cars still exceeds the TCO of combustion engine cars by approximately 25-30% [5]. When it comes to range issues, a journey beyond the car's range must undoubtedly take into account the need to recharge. However, it should also be noted that relatively few journeys exceed this range, especially for micro-enterprises. Therefore, the question is whether this argument is based on real experience with electric cars or whether it stems more from a lack of experience [6]. As for the objection regarding the limited infrastructure for electric car charging , the question arises as to whether this is of great importance to micro-entrepreneurs in Poland, given that a combination of own photovoltaics and electric cars is widespread there.

It seems that all three arguments can be overcome with an appropriate system of legal and tax incentives, if they were to cover micro-entrepreneurs. Polish incentives in 2025 included excise duty exemptions, depreciation limits, and VAT deductions. However, these incentives were not explicitly targeted at micro-enterprises, but rather at individuals and large entities making infrastructure investments. In short, capital constraints for microenterprises were ignored, except for sole proprietorships, where the incentives covered only leasing and rental.

The above discussion raises two key questions that remain unanswered: (1) What barriers prevent Polish MEs from adopting BEVs despite at least partial incentives, and how do the characteristics of MEs reinforce these barriers? (2) Which fiscal/regulatory incentives are most effective in increasing popularity among MEs?

Given the extremely low number of publications on microenterprises, the topic should be treated as a research gap. To fill this gap, this study analysed opinions on BEVs and the effectiveness of incentives using a CAWI survey conducted among 307 small and medium-sized enterprises from the Małopolska region. The hypothesis that the most important incentives for micro-enterprises are subsidies, free parking in city centres and free city access to low-emission zones was tested.

The contribution of this publication to the literature on electromobility and scientific novum includes empirical confirmation of barriers to electric vehicles in Poland, the need to enrich policy design with subsidies specifically for electric vehicles and chargers in rural areas, and the development of RBV theory by taking into account human/and institutional factors in the process of implementing sustainable transport. This is of significant importance for the 353,300 electric vehicles driving the Polish economy.

2   Literature review

In recent years, more and more companies, including micro-enterprises, have begun considering purchasing electric cars. However, while about 1% of small businesses already own an electric car, the figure is much lower for micro-enterprises, with electric vehicles a rare sight in this [7]. Research by Shub et al. [7] suggests that the low popularity of electric cars among this group may be due to concerns about three key issues: high purchase costs, range, and access to charging. These concerns will be addressed in light of the results of other studies.

Regarding the argument about purchase costs, the research results are inconclusive. According to Parker et al. [5], for households in the US, the cost of owning an electric car for five years does indeed exceed the cost of ownership of a combustion car by approximately 25-30% (based on the typical mileage of a family car in the US, i.e., 19,300 km per year). This thesis is also confirmed by research conducted by Xu Hao and et al. (2020) [3], who showed that in China, electric cars with a range of up to 250 km had a lower total cost of ownership only in cities with restrictions on combustion cars, and electric cars with a range of up to 450 km had a lower TCO only in cities with a cold climate. In other variants, combustion engine cars had a lower TCO.

However, research by Soszyńska et al., conducted three years later [2] for North America, shows that thanks to government subsidies, cheaper energy, and lower service costs, the higher purchase costs of BEVs were offset by cheaper operating costs, resulting in a lower TCO than combustion engine cars over a five-year period. Similar conclusions were also reached by Figenbaum [4], who conducted research in Norway, and by Hagman et al. [8], who conducted research in Sweden. Figenbaum's research showed that, thanks to a combination of factors, electric cars in Norway had been cheaper than combustion engine cars since 2012. These factors included: exemption from registration tax (since 1990), exemption from VAT (since 2001), exemption or reduction of annual insurance tax, free or cheap access to toll roads, parking lots and ferries, access to bus lanes, cheaper electricity than fuel, lower service costs, falling battery prices, increased range and availability of fast charging stations, and a long-term and stable BEV support policy. Hagman et al. [8] reached similar conclusions for Sweden.

In Poland, an interesting experiment was conducted by WebFleet in cooperation with EV Klub Polska, in which four electric cars were tested at small companies powered by their own photovoltaic installations. Over the course of a year, each car traveled approximately 24,000 kilometers and saved approximately PLN 15,000 in fuel costs. Even if the price difference between a combustion engine car and an electric car was PLN 75,000, after five years of such driving, the electric car costs the same as the combustion engine car [9]. Due to the motor's greater durability and the easier replacement of individual motors at the wheels, even if the battery had to be replaced every 8-10 years, the subsequent savings would still compensate for this. Nevertheless, in light of changes in regulations concerning private photovoltaic networks and reducing their profitability, an important observation arises: the decline in the financial efficiency of

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photovoltaic installations may reduce the profitability of electric cars in Poland, as in the experiment by Kania and Wisniewski [9], electricity from their own installation was a significant element of the cost advantage of such cars.

In summary, regulations, tax breaks, and the research method strongly influence the profitability of electric cars. Electric cars are undoubtedly more expensive, while their operating costs are lower. In many Western countries, tax incentives are very high, making these cars quickly more cost-effective than combustion-engine cars. However, even without subsidies, an electric car makes economic sense if you have your own photovoltaic installation. So, the first argument against electric cars is valid in terms of purchase costs, but with the right infrastructure providing cheap electricity, the higher purchase costs are quickly offset by lower refueling costs. However, this cheap electricity must not become more expensive.

The second argument often cited by micro-enterprises against purchasing electric cars is the short range of electric cars. However, these ranges have increased significantly over the last 15 years and are now three times longer than before – standard electric cars achieve an average of 300 to 450 kilometers, and long-range cars 500 to 700 km. Comparing these distances with the typical daily journeys of micro-entrepreneurs, it is hard not to notice that such ranges should be sufficient.

Numerous empirical sources show that the vast majority of micro-enterprises operate in the local market, and their range of activity is usually limited to travel within the city or the immediate vicinity, with commutes lasting approximately 15-30 minutes. This can be translated into a distance not exceeding 30 kilometers from the company's headquarters. However, sometimes there can be a large number of such trips, for example, in the case of services representing elements of logistics (typical types of activities related to micro-enterprises in which many kilometers are traveled daily):

- courier services involving flows,
- delivery as flow, management, or material,
- local and regional transport with technical elements of logistics,
- mobile services (e.g., repairs, tire repair, cleaning).

In practice, the average courier optimising logistics travels about 31 km per day for meal deliveries in the city (occasionally up to 120 km) [10,11]. For car couriers who deliver parcels, daily mileage can range from around 100 km to as much as 300 km, especially outside the city [11,12]. Bicycle couriers in large cities can travel an average of 70 km per day, up to 80 km [11].

Urban delivery vehicles managing flow or management of financial through efficient routes typically cover distances of approximately 70 km to 300 km per day, depending on the nature of the work and the delivery area. For comparison, heavy trucks travel up to 500 km per day [13]. Therefore, electric urban delivery vehicles, which usually have a range of 150-200 km per day, meet the needs of couriers or delivery drivers in the city.

In the case of regional transport, a bus covering such routes travels between 9,000 km and 15,000 km per year, which gives a daily mileage of 40-60 km. As was also the case with delivery and courier companies, the range of electric cars also meets these needs [13].

However, it must be admitted that electric cars have limitations in range, so on long journeys, the need to recharge the battery returns. We will come back to this issue a little later.

According to Msosa [1], the third argument against purchasing an electric car, often raised by micro-enterprises, is concern about access to charging stations. Indeed, the network of charging stations in Poland is less developed than in Western European countries such as Germany, France, the Netherlands, or Norway [14], but it is quite well developed in large cities [15] and the ratio of electric cars to charging stations is one of the best in Europe. The cost of charging at such a station is also one of the lowest in Europe [15]. Therefore, this argument does not seem to be a real obstacle. In addition, the company can charge cars at night and replace batteries as needed (quick replacements). Indeed, the experiment described by Kania and Wisniewski [9] confirms an average charging time of 2.5 hours as too long compared to expectations (20 minutes), but the experiment also showed that the cars did not drive long enough for this to be a problem – they stood between routes in parking lots long enough that they could easily be charged for 2.5 hours. In addition, the cars were mainly charged at night from their own photovoltaic installation. Therefore, despite the existence of ultra-fast chargers (where charging from 20% to 80% takes 15 to 30 minutes), their availability in Poland is not yet sufficient for entrepreneurs to have no legitimate concerns that they will need to carefully plan long routes to access fast chargers. This suggests the first important incentive for drivers in the form of expanding the charger infrastructure to provide full coverage of the road network in Poland – they do not necessarily have to be at gas stations, as a suitable app is enough to find them (e.g., Plugshare, ChargePoint, Chargemap, Ultra-Fast by ADS-TEC Energy, PowerX App, Google Maps).

Other reasons for micro-enterprises' reluctance to use electric vehicles are given by Badowski et al. [6]. Their research, based on a panel of micro-entrepreneurs from Poland, showed that the most important factor encouraging or discouraging the purchase of electric cars was access to information and knowledge about electric vehicles, followed by financial costs and benefits. A significant increase in interest in electric vehicles occurred after the COVID-19 pandemic, likely due to the rapid growth of last-mile deliveries during this period and the broader dissemination of information about electric cars resulting from European Union policy [16]. This argument seems quite valid, given certain characteristics of the

investment process in microenterprises. This, in turn, allows us to develop another proposal to enhance the attractiveness of electric cars, namely, appropriate training for micro-entrepreneurs and the dissemination of reliable and comprehensive information about electric cars and their operation.

According to our conversations with small business owners, such entities often find it more difficult to obtain the necessary funds for the purchase, even if they are later recouped through cheaper fuel costs, greater conservatism and reliance on tried and tested technologies for fear of problems that decision-makers may not be aware of, and a strong dependence of investment decisions on the opinion of the owner, who often has conservative views (even though other employees may want to purchase electric vehicles). This is a common problem for micro-enterprises concerning all micro-enterprise investments, affecting all investments requiring credit financing (short history, lack of collateral, high credit costs, high vulnerability to economic changes) [17-19]. This, in turn, shows that another factor that can positively influence the purchase of electric cars is support for investment loans (which is partly implemented, among others, by the Polish NaszEauto program supporting the rental and leasing of electric cars for sole proprietorships, which very often belong to the group of micro-enterprises, and a program of preferential loans for micro-enterprises with long repayment periods).

In addition, microenterprises are usually highly concentrated around the owner-founder, who personally manages most of the company. In small and medium-sized enterprises, the structure is more complex, with separate functions and formal management processes. Therefore, the decision to purchase an electric car depends on the views of one person [20]. A single person burdened with so much work in the company does not have time to develop their knowledge about electric cars.

According to the research by Majchrzak and Ratajczak-Mrozek [20], micro-enterprises are less inclined and less capable of implementing new technologies (for the reasons outlined above). Due to capital constraints and limited knowledge, micro-enterprises are more conservative about investing in EVs and more sensitive to current operational barriers (e.g., access to chargers) because they operate in a small geographic area [21].

Research by Majchrzak and Ratajczak-Mrozek [20] also shows that micro-enterprises often operate more reactively, focusing on current needs rather than long-term planning, which hinders the implementation of new technologies requiring a strategic approach, such as EVs [20].

In addition, micro-enterprises are more concerned about initial costs and operational barriers (e.g., charging), as many of them quickly cease to exist, while small and medium-sized enterprises often see greater benefits from lower operating costs [20].

Small and medium-sized companies are more willing to implement EVs in their fleets, using leasing, support systems, and long-term cost-effectiveness strategies. Microenterprises often lack such opportunities [20]. If they are treated the same way as the SME sector, which offers much greater financial opportunities, micro-enterprises have no chance of purchasing electric vehicles [22]. This, in turn, leads to another element of motivating the purchase of EVs: taking into account the specific nature of micro-enterprises and not treating them simply as part of SMEs (this is partially implemented by the NaszEauto program). Therefore, as the research results show, micro-enterprises have specific characteristics, indicating that programs designed to support EV adoption must be tailored to their needs and capabilities.

In addition to limited access to capital and infrastructure barriers, micro-enterprises also face the following problems:

- Lack of human resources and skills: Micro-enterprises often do not have specialized staff, which limits their ability to manage innovation and technological change, including the implementation of electromobility or new IT solutions [21].
- High level of market uncertainty: Due to their smaller scale of operation and shorter history, micro-enterprises are more exposed to market volatility and find it more difficult to cope with it; hence, they choose investments with a short return period, and EVs do not fall into this category [23,24].
- Complex legal and administrative procedures: Micro-enterprises often find it difficult to navigate the bureaucracy and formalities associated with grants, tax breaks, or support programs, which can discourage them from taking advantage of available forms of assistance [18].
- Short-term perspective: Focusing on current, immediate needs leads to a lack of sufficient strategic planning, which hinders development and adaptation to change [25].
- Strong dependence on the owner: Decisions are often centralized and dependent on the individual views of the owner, which can slow down decision-making processes and limit the adoption of new ideas [26,27].

Summing up, micro-enterprises commonly face flow or financial management constraints together with limitations on human flows, requiring technical elements of logistics adaptation.

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3   Methodology

3.1   *Electric car purchase support programs available to micro-enterprises in 2025*

In Poland in 2025, numerous regulations and support programs for electric car users were designed to encourage companies to electrify their fleets.

An important institution for the development of electromobility in 2025 was the National Fund for Environmental Protection and Water Management (NFOŚiGW), which managed programs financed from national funds, the National Recovery Plan (KPO), and the Modernization Fund.

In 2025, when purchasing an electric car, it was possible to benefit from tax reliefs such as an exemption from road tax, discounts on registration tax, and the possibility of deducting VAT.

In particular, when purchasing an electric car [28], micro-entrepreneurs could count on:

- exemption from excise duty when purchasing an electric car,
- the possibility of taking advantage of a higher depreciation limit for entrepreneurs,
- VAT deduction for investments in electromobility,
- tax relief for individuals and companies investing in charging infrastructure,
- financial support from the National Fund for Environmental Protection and Water Management (NFOŚiGW), the National Development Plan (KPO), and the Modernization Fund, and financial support for expanding the charging infrastructure.

In 2025, new regulations were also introduced requiring the installation of charging points in new commercial buildings, intended to increase the availability of infrastructure for companies.

In 2025, sole traders were eligible for PLN 30,000 in support for leasing or long-term rental of an electric vehicle under the "NaszEauto" program, which was a continuation of the "Mój Elektryk" program but with a new, less favorable formula for entrepreneurs.

The previous "Mój Elektryk" program subsidized the purchase of electric cars for companies, including micro-entrepreneurs (it operated from November 22, 2021, to December 31, 2024, although application acceptance was suspended on September 1, 2024).

Under the "NaszEauto" program, sole traders could receive PLN 30,000 in subsidies for leasing or renting an electric car, provided the net price did not exceed PLN 225,000. In addition to the PLN 30,000 subsidy, sole proprietorships could also receive a PLN 10,000 bonus for scrapping a vehicle. The total amount of the subsidy could not exceed PLN 40,000. In the case of leasing or rental, the contract must be valid for at least 2 years [29].

In addition to direct subsidies, another form of support for the development of electromobility, including among micro-enterprises, was the subsidization of the expansion of electric vehicle charging infrastructure. Programs operating in Poland focused on creating high-power public stations and points for heavy transport.

Distribution system operators could obtain support covering up to 100% of eligible costs for the construction or modernization of power grids necessary for charging station operation, with a particular focus on the country's main arteries [30]. Similarly high support could be obtained by entrepreneurs installing chargers for heavy goods vehicles (up to 85% in the project finance model). The programs also covered large companies producing components for the electromobility sector, including chargers, energy management systems, and energy infrastructure elements [30].

Unfortunately, in 2025, projects to subsidize charging network construction focused only on public or commercial projects and did not include subsidies for private charging points intended for individuals or small businesses. Nevertheless, publicly accessible charging stations were intended to support electromobility also for micro-enterprises (with the possibility of including such costs as tax-deductible expenses) [29].

In addition to programs supporting electromobility through subsidies, favorable tax regulations were also applied. The most important relief for entrepreneurs was the exemption of electric cars and hydrogen-powered vehicles from excise duty. In addition, plug-in hybrids were subject to lower excise duty rates than traditional combustion engine cars (until 2029) [30].

In 2025, companies using electric cars also had the option to set a higher depreciation limit – in their case, up to PLN 225,000 - while for combustion engine vehicles the limit was only PLN 150,000 [29].

Another tax benefit for companies using electric cars was the ability to deduct VAT on expenses related to their purchase. If the vehicle was used for both business and private purposes, half of the VAT was deductible. However, if the car was used exclusively for business purposes and met certain criteria, it was possible to deduct 100 percent of the VAT [29].

Yet another tax relief offered in connection with the development of electromobility was the possibility of treating the costs of building charging stations as income-generating expenses and, for VAT purposes, deducting them under standard rules. This applied to both individuals and businesses [30].

If we were to point out the limitations of the programs described, we would note a few key points. In the "NaszEauto" program, the car's value could not exceed PLN 225,000 (approx. EUR 53,000), and it had to be new or a demonstration

model with a maximum mileage of 6,000 km. The program's funds were limited, and applications were considered on a first-come, first-served basis until the budget was exhausted. The subsidy was provided on a reimbursement basis, i.e., the entity first had to obtain sufficient funds to make the purchase, and only then could it apply for a refund (the costs were reimbursed only after the applicant had paid the entire amount [30].

Another drawback of the electromobility support programs from the perspective of micro-enterprises was that funding for charging infrastructure and charging station construction was directed exclusively to public and commercial investments, and therefore went only to larger entities implementing projects relevant to the public network. The subsidy programs also did not provide for subsidies for used vehicles or cars imported from outside the EU, nor did they apply to vehicles previously registered to other companies or individuals [30].

3.2 Description of the research method

As part of their research, the authors prepared a survey to determine the main reasons for micro-entrepreneurs' reluctance to purchase electric cars and the possible incentives that would effectively remove these barriers. To this end, the authors used a research questionnaire to gather opinions from micro-enterprises on the usefulness of electric cars, their plans to purchase them, their experiences with them, and the perceived advantages and disadvantages of such vehicles. The survey was conducted using the CAWI (Computer-Assisted Web Interview) method, which involves conducting online surveys. The authors sent requests electronically and by telephone, and the average response rate was approximately 0.5%. Respondents completed the questionnaires online themselves. Ultimately, surveys were collected from 307 participants representing various business sectors in Poland.

4 Results

A total of 307 people working in micro-enterprises in the Małopolska Province provided useful responses in the survey (according to the Central Statistical Office in Małopolska, there were approximately 353,300 active micro-enterprises in 2024). Figure 1 shows the gender structure. When selecting respondents, we tried to maintain proportions appropriate to the issue being analyzed. We originally planned to maintain a 30:70 ratio (the ratio of women to men in terms of microenterprise ownership), but due to the difficulty in reaching owners, we focused on employees of microenterprises involved in investment decisions and therefore maintained a 50:50 ratio (women to men), as this is the gender structure of people of working age in Poland. In terms of the number of respondents, we collected a sample representative at the 90% significance level (i.e., with a margin of error of 10%).
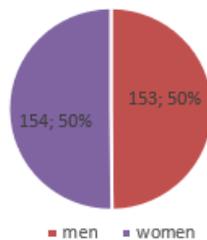
Figure 1 Gender structure of the respondents (out of 307 respondents)

As for the age structure of the respondents, we did not have accurate statistics on the age of micro-enterprise employees, apart from information (from PARP) that the average age of people working in the micro-enterprise sector exceeded 40 years (Figure 2). Therefore, we aimed to ensure that at least half of the research sample consisted of individuals aged 40 or older.
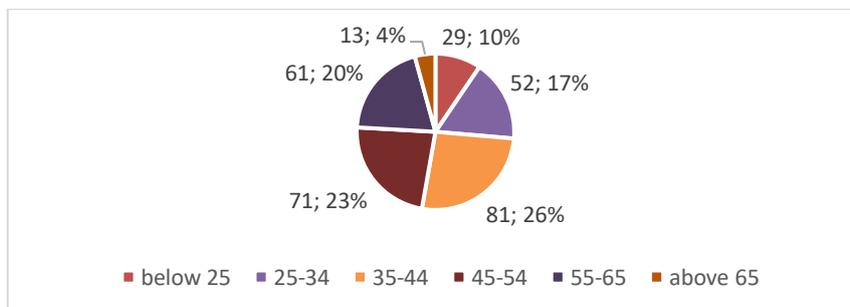
Figure 2 Age structure of respondents

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Similarly, given the population structure of the Małopolska Province, we adjusted the research sample to reflect the rural-to-urban ratio. According to data from the Central Statistical Office (GUS), approximately 52% of the population of Małopolska Province lived in rural areas, with the remainder living in cities (Figure 3).
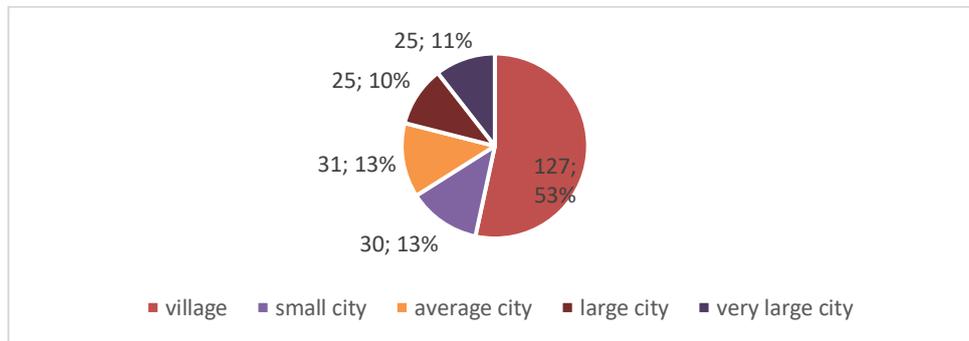
Figure 3 Place of residence of respondents (rural or urban)

Figure 4 and Figure 5 show the distribution of responses to the question about access to a car in a microenterprise. Respondents could give several answers, which is why they do not add up to 307 (a total of 341 responses were given). The most common response among respondents (41.1%, or 140 responses) was that the company had its own cars. The second most common response was no car (27.6% of responses; 88% of respondents said the company had no need for one, and the rest said there was no money for one), and the third was leasing (19.9% of responses). The least common responses were the use of employees' cars (6.5%) and rental (5%). In two cases, respondents added that although the company did not own any cars, it used taxis.
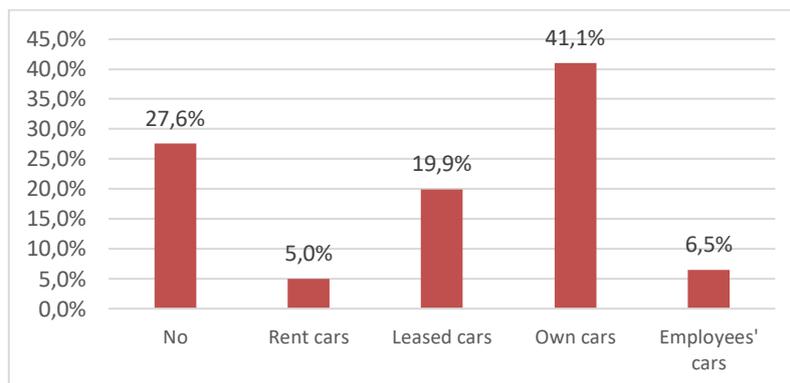
Figure 4 Access to a car in a microenterprise
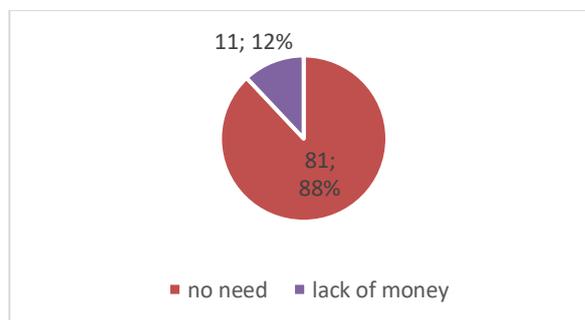
Figure 5 Reasons for not having a car in the company

When asked about the means of transport used by the company, we received 484 responses, as respondents could select multiple answers. The most common types of transport used by the micro-enterprises surveyed were passenger cars (41.3% of responses) and delivery vans up to 3.5t (20.7% of responses). The third most popular means of transport among the surveyed companies was trucks over 3.5t (10.3% of responses), followed by trains (also 10.3% of responses). Finally, 5% of responses were for planes, motorcycles and scooters, and bicycles. Only 1.9% of responses were for special-purpose vehicles (Figure 6).
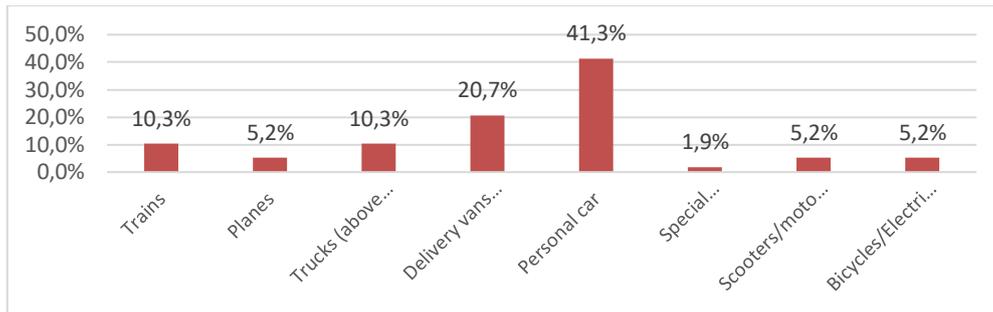
Figure 6 Types of transport used by the company

Figure 7 shows the distribution of responses to the question of the range of 95% of journeys made as part of the company's operations (a total of 307 responses were provided). The distribution of responses shows that most respondents traveled a maximum of 100 km from their headquarters (29%), followed by trips within the city (village) and trips of less than 20 km (20% each). To summarize the responses, 84.4% of flows were below 300 km from the headquarters, routes that can be covered by an electric car. Only 15.6% of responses indicated routes that may be too long for a typical electric car (however, only 6.2% of responses exceed the range of a long-range electric car).
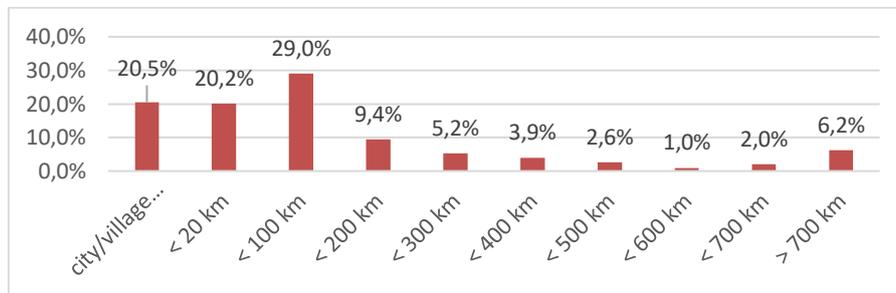
Figure 7 A range of 95% of routes in relation to the headquarters

Figure 8 shows the distribution of responses (1,537 in total) regarding the criteria used by companies when purchasing or leasing (or renting) a car. As can be seen from the responses, the most important criteria were reliability (10.9%, or 167 responses), cost-effectiveness (10%, or 154 responses), and a positive experience or opinion (8.4%, or 129 responses). Other important factors in choosing a car were: covering long distances without breaks or problems (7.5%, 115 responses), durability (7.2%, 111 responses), large luggage space (6.8%, 104 responses), and low price (5.7%, 88 responses). The responses indicate that the primary criteria for choosing a car were not price, but good reputation, reliability, and the ability to cover long distances easily. The question of what micro-entrepreneurs understand as a long distance remains open to discussion, given that 84.4% of them do not travel more than 300 km from their headquarters on 95% of their journeys. However, it is likely that this refers to the potential to make very long journeys if the need arises, which is not currently a strong point of electric cars – they allow for long journeys, but require stopping to recharge the battery. Respondents also added their own criteria: brand preferences, engine power, the number of kilometers a given model will travel during its lifetime (to suit the company's needs), and appearance.
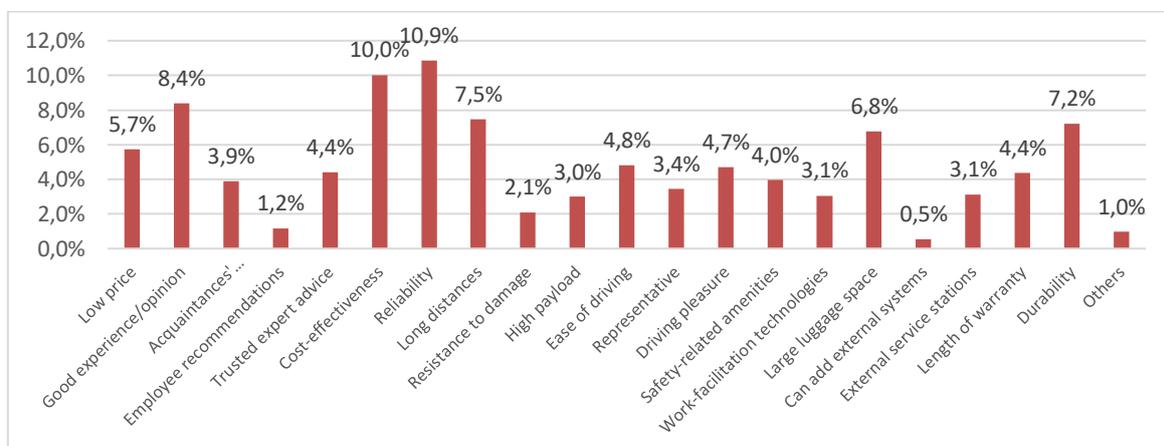
Figure 8 Criteria for choosing a car when buying or leasing (or renting)

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Figure 9 shows the distribution of respondents' opinions on electric cars. As can be seen from the responses, the majority of respondents (65%) believed that hybrid electric vehicles are good, but inferior to electric cars. 14% of respondents had a negative opinion of electric cars, and 21% believed they are better than combustion-engine cars.
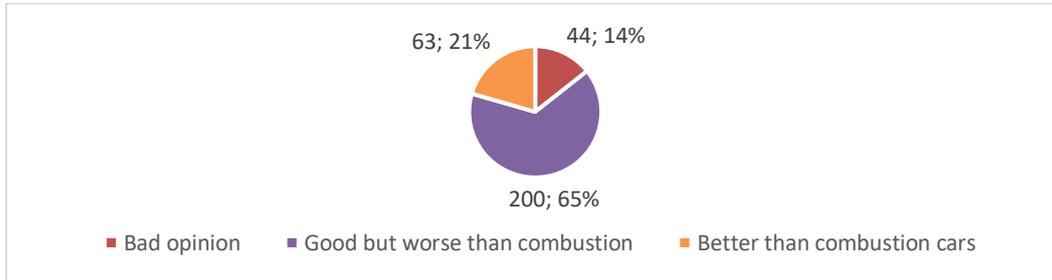
Figure 9 Opinion on electric cars

Figure 10 shows the distribution of responses regarding the advantages of electric cars. In total, respondents gave 938 responses (multiple answers were possible). The most common advantages (15.1% of responses) were low daily running costs, environmental friendliness (13.9%), ease of driving (10.9%), technologies that make work easier (9.7%), safety features (9.4%), and driving pleasure (9.3%). Those who answered the previous question that they had a negative opinion of electric cars listed the following as advantages: environmental friendliness, representativeness (worthy representation of the company), long-term financial profitability, cost-effectiveness in everyday use, ease of driving, warranty length, safety features, and driving pleasure. These respondents did not mention long-distance driving, reliability, or low price as advantages (in general, such responses were rare). Some of them indicated a complete lack of advantages. Respondents cited comfort and modern interior, noise reduction, quiet operation, free parking in the city center, and higher cost deduction limits as additional advantages.
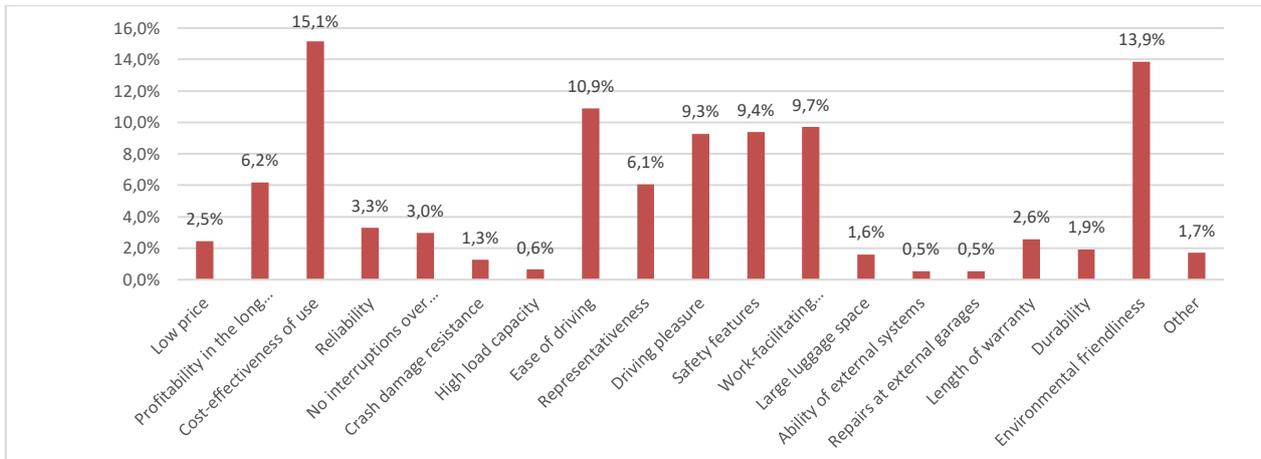
Figure 1 Advantages of electric cars

Figure 11 shows the distribution of respondents' opinions on the statement that electric cars are very impractical because they require frequent charging. As shown in Figure 11, 65% of respondents considered this statement to be true.
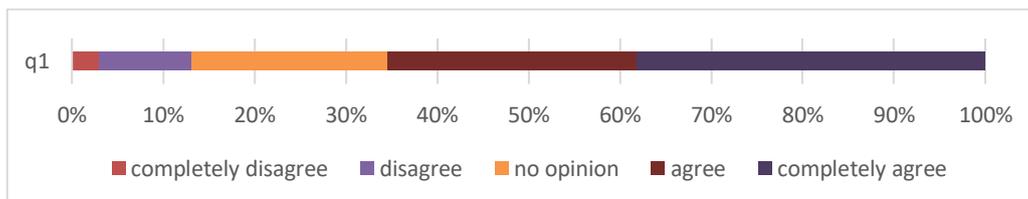
Figure 2 Electric cars are very impractical due to the need for frequent charging

Figure 12 shows the distribution of respondents' opinions on the statement that using an electric car requires careful trip planning. As shown in Figure 12, 75% of respondents considered this statement to be true.
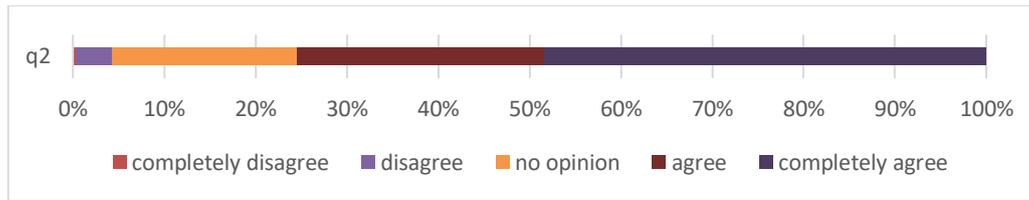
Figure 3 Using an electric car requires careful trip planning

Figure 13 shows respondents' opinions on the likelihood of losing range in an electric car and the costs of emergency charging. 69% of respondents agreed with this statement.
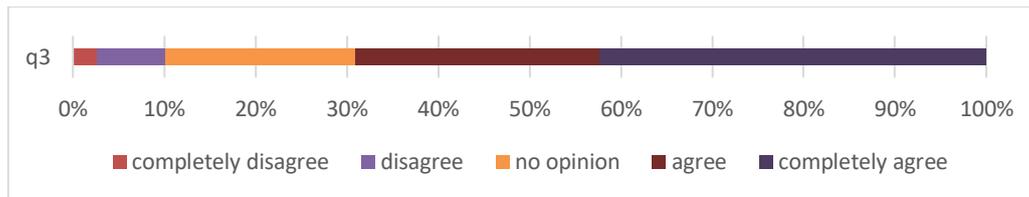
Figure 4 Fear of losing range in an electric car and the costs associated with emergency charging

Figure 14 shows the distribution of respondents' opinions on the excessive charging time of electric cars during long journeys. 75% of respondents agreed with this opinion.
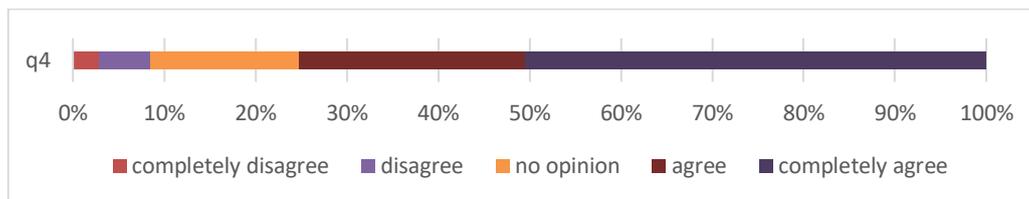
Figure 5 Charging an electric car during a trip takes too long

Figure 15 shows the distribution of respondents' opinions on the insufficient number of charging stations in Poland. Over 78% of respondents agreed with this statement.
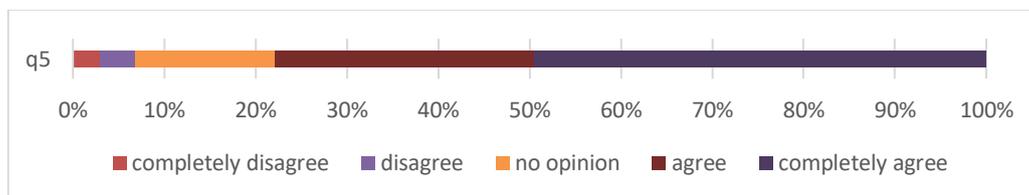
Figure 6 Insufficient number of charging stations to purchase an electric car

Figure 16 shows respondents' opinions on the cost of installing electric-car charging stations. 49% of respondents agreed with this statement. Therefore, the respondents do not fully agree with this opinion.
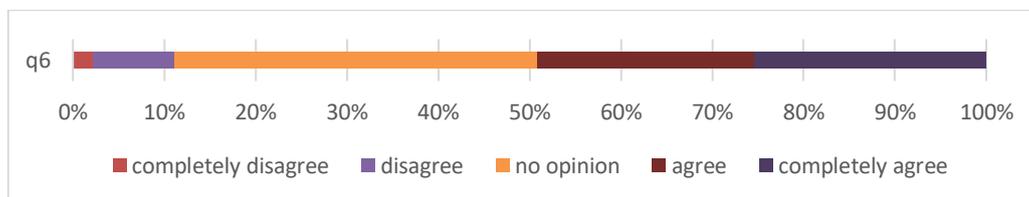
Figure 7 Very high costs of creating electric car charging stations

Figure 17 shows respondents' opinions on the increase in electricity bills caused by driving an electric car. 64% of respondents agreed with this statement.
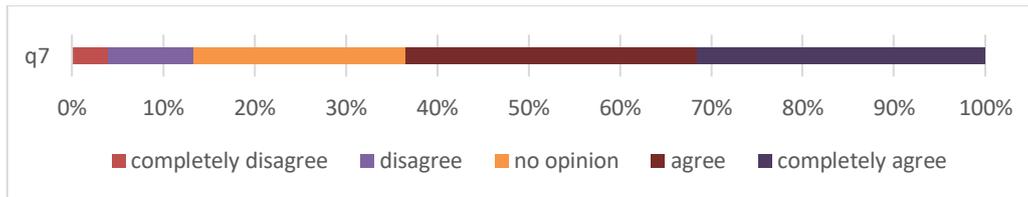
Figure 8 Using an electric car is associated with increased electricity bills

Figure 18 shows respondents' opinions on the risk of fire in electric cars. Concerns about fire were reported by 55% of respondents.
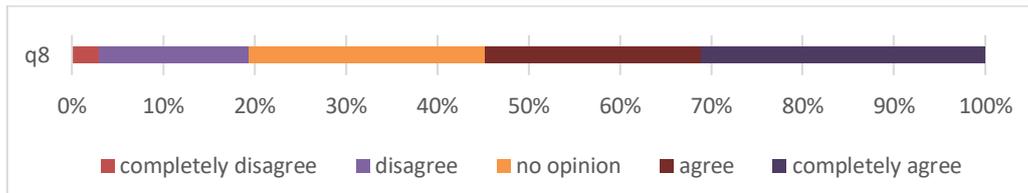
Figure 9 Fire risk when using an electric car

Figure 19 shows that 53% of respondents have doubts about the environmental friendliness of electric cars because electricity is generated from coal and oil.
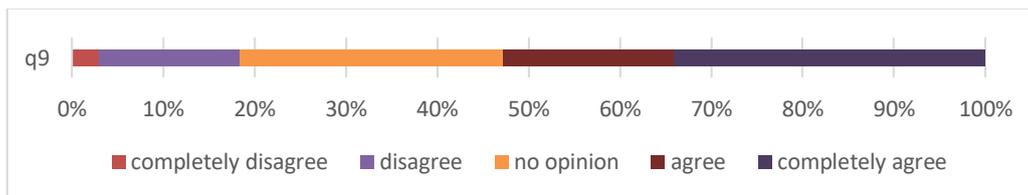
Figure 10 Doubts about the environmental friendliness of electric cars due to the production of electricity from coal and oil

Figure 20 shows that 66% of respondents are concerned about the environmental impact of battery disposal and believe that this reduces the environmental friendliness of electric cars.
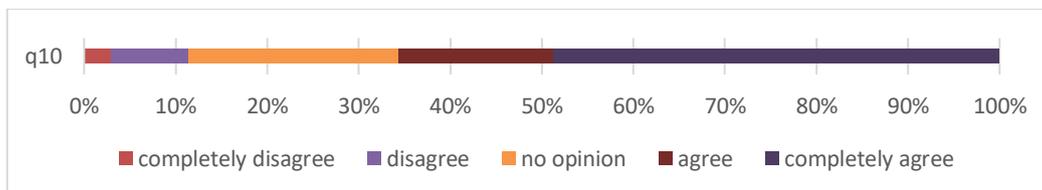
Figure 11 Doubts about the environmental friendliness of electric cars due to the need to dispose of batteries

Figure 21 shows the distribution of respondents' opinions on the durability of electric-car batteries. As can be seen in Figure 21, 69% of respondents had such concerns.
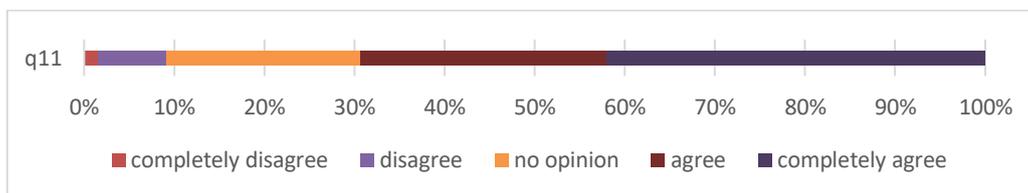
Figure 12 Batteries in electric cars are expensive, and it is not known how long they will last in cold climates

Figure 22 shows the distribution of responses regarding the purchase price of electric cars. As shown in Figure 22, 56% of respondents believe they are still too expensive.

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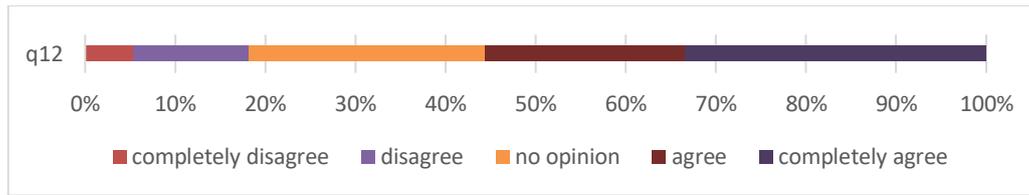
Figure 13 The purchase price of an electric car is too high

Figure 23 shows that 66% of respondents fear that as the number of electric car users increases, electricity prices will rise, making the purchase of such cars less and less profitable.
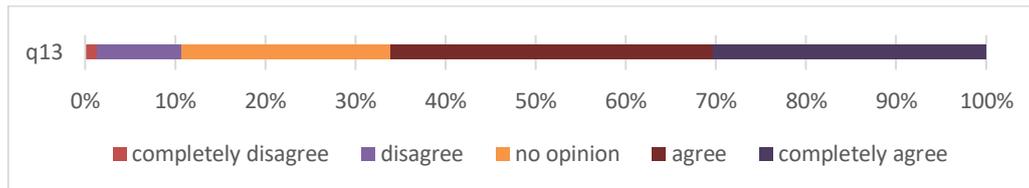
Figure 14 The risk of energy price increases limits the appeal of electric cars

Figure 24 shows that 56% of respondents were concerned about the depreciation of electric cars. Devaluation results, among other things, from technological progress, which causes older versions to quickly lose value, concerns about battery life, uncertainty about resale (the electric car market is less predictable than the combustion engine car market), and the rapid impact of subsidies and government programs on supply and demand.
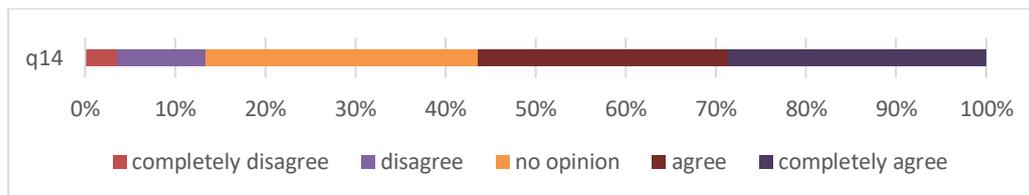
Figure 15 There is a high risk that an electric car purchased today would quickly depreciate

Figure 25 shows the distribution of respondents' answers regarding problems with finding electric car repair shops. 66% of respondents agreed with this opinion.
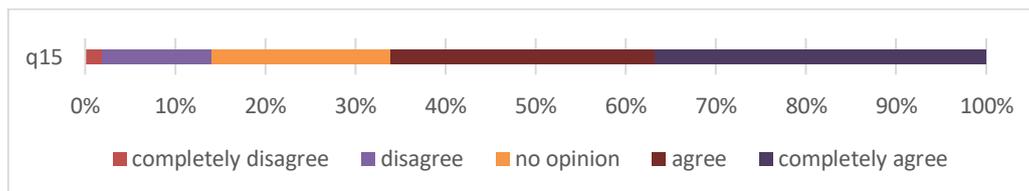
Figure 16 Few electric car repair shops

Figure 26 shows that only 22% of respondents believe that electric cars have poor acceleration. As these cars generally have very good acceleration, this shows that respondents have a relatively good understanding of e-car technology.
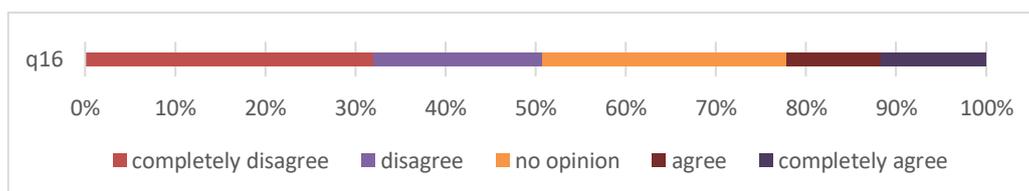
Figure 17 Electric cars do not have sufficient acceleration

Figure 27 shows that only 42% of respondents believe that electric cars offer less driving pleasure than combustion engine cars because they are silent. For most respondents, this was not important.

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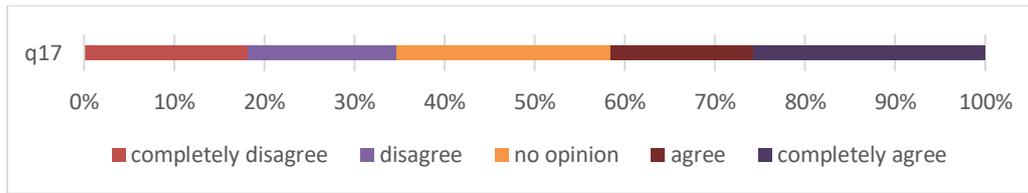
Figure 18 Less driving pleasure than a combustion engine car

Figure 28 shows what respondents consider the advantages of electric cars over combustion-engine cars. Because respondents could provide multiple answers, a total of 1,218 responses were collected. Most respondents believed that the biggest advantage of electric cars is that they can be parked for free (12.8% of responses), no noise (12.5%), the ability to use bus lanes (12.4%), the ability to enter city centers (12%), and subsidies, grants, and tax breaks (8.5%).
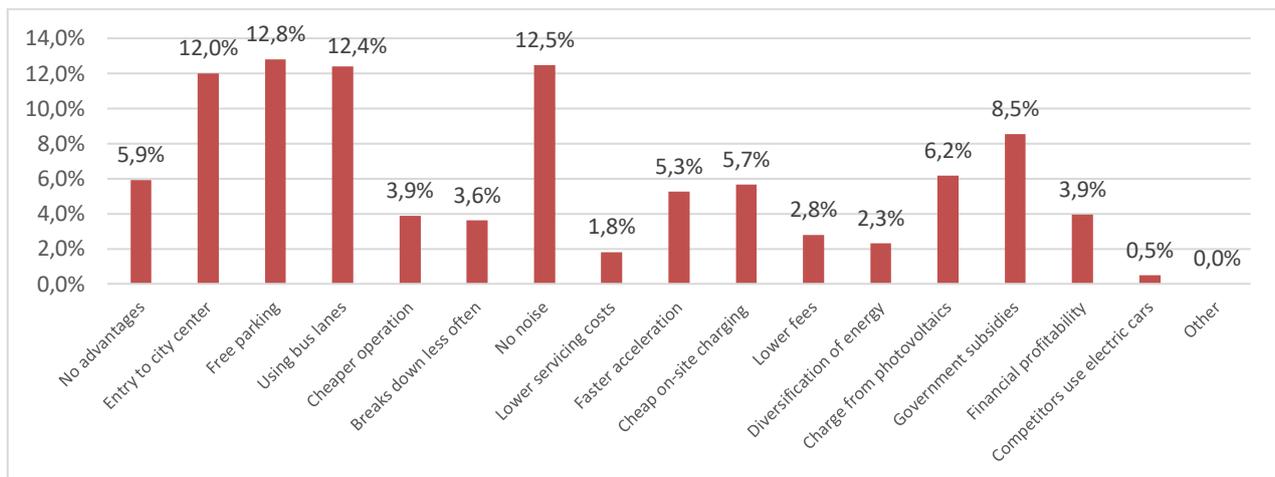
Figure 19 Advantages of electric cars over combustion engine cars

Figure 29 shows the most important advantages of combustion-engine cars compared to electric cars (1,158 respondents). As shown in Figure 29, the most important factors are trouble-free and quick refueling (18.9% of responses), a lower purchase price (17.9%), easier repairs and servicing (16.5%), and cheaper parts (16.4%).
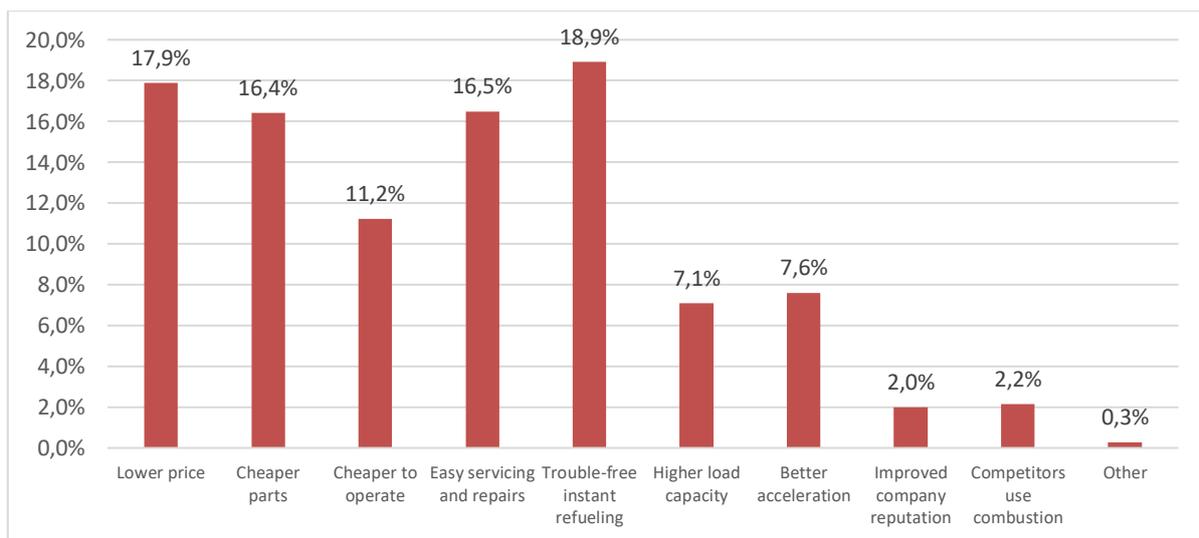
Figure 20 Advantages of combustion engine cars over electric cars

Among 307 respondents, 20.5% have purchased (1%) or plan (19.5%) to purchase a passenger electric car, and 7.5% have purchased (1%) or plan (6.5%) to purchase a delivery vehicle. One company also purchased an electric bicycle. The comments in the survey showed that the main reasons were the possibility of entering the city center (mainly the inability to enter with combustion engine cars and the fear that the zone would expand) and free parking, lower registration fees,

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subsidies, tax breaks, a very good offer (better than for a combustion engine car), the possibility of charging from photovoltaic panels, engine durability, the desire to try out such cars, and convenience. The most frequently repeated arguments were: the possibility of entering the city center, tax breaks, subsidies, and grants (until the end of 2024, companies could participate in a program to subsidize such cars), and the cost-effectiveness of this technology when using their own photovoltaic cells.

Table 1 shows the distribution of responses to the question of which incentives, in respondents' opinions, are most likely to encourage the purchase of an electric car. Unfortunately, some respondents did not read that they were asked to indicate a maximum of 5 incentives, and some marked more. The most popular incentives were the electric car subsidy program (up to PLN 40,000, 8.5% of responses), free or cheaper parking in city centers (7.5% of responses), grants for the purchase of electric cars (7% of responses), access to bus lanes (6.5%), tax exemptions (6.4%), lower motorway tolls (4.4%), access to city centers (4%), and subsidies and exemptions from registration fees (3.5%). The exact distribution of responses is presented in Table 1.

Table 1 List of the most desirable incentives for purchasing an electric car

Facility	Votes	Percentage
Grant program for electric car purchase up to PLN 40,000	166	8.5
Free or discounted parking in cities	147	7.5
Grants for electric car purchase (lump sum or percentage)	138	7.0
Access to bus lanes	127	6.5
VAT exemption for electric car purchases (no VAT on EV purchase)	125	6.4
Personal Income Tax (PIT) deductions	119	6.1
Lower road or highway fees for EVs	87	4.4
Entry to low-emission zones (where combustion vehicles are banned or charged)	79	4.0
Subsidies for electric cars to equalize their price with combustion vehicles	69	3.5
Exemption from or reduction of registration fees	69	3.5
Tax reliefs for leasing	60	3.1
Excise tax exemption for electric car purchases	58	3.0
No such incentives	53	2.7
Cheap electricity from renewable energy sources	52	2.7
Higher depreciation limits for entrepreneurs or VAT deductions	45	2.3
Grants for building charging stations (for companies and local governments)	42	2.1
No import duties	42	2.1
Free ferries, highway toll discounts	41	2.1
Fast EV charging stations at every gas station in Poland	40	2.0
Fast EV charging stations at every gas station in the EU	37	1.9
EV charging stations at every gas station in Europe	35	1.8
Tax reliefs for companies leasing electric vehicles	35	1.8
EV charging stations at every gas station in Poland	34	1.7
Fast EV charging stations at every gas station in Europe	34	1.7
Higher taxes on combustion engine vehicles	31	1.6
Tax credit up to PLN 30,000	29	1.5
Massive investments in charging infrastructure	27	1.4
Developed the battery industry and cheap domestic electricity	24	1.2
Charging stations at borders (where customs clearance takes place)	21	1.1
Bonus for scrapping a combustion engine car (an extra PLN 5,000 for an electric car purchase)	21	1.1
Charging stations at our main customers (target locations where we travel)	17	0.9
Ban on buying electric cars in 2035	16	0.8
For high mileage, an electric car pays off twice as fast as a combustion car	14	0.7
Preferences in public procurement (postal fleets, buses)	12	0.6
Registration restrictions for combustion cars in big cities (license plate lotteries)	11	0.6
Increasing restrictions for EVs	5	0.3

Figure 30 shows the distribution of respondents' answers to the question about the maximum acceptable charging time for an electric car during a trip. The most popular answers were 15 minutes (45.4%) and 5 minutes (33.8%). Each respondent could choose only one answer.

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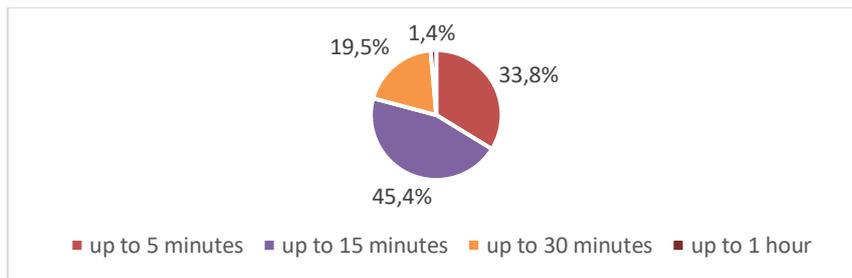
Figure 21 Maximum acceptable battery charging time during a trip

Table 2 shows the distribution of responses to the last question in the survey, which asked about the reasons for lack of interest in electric cars (purchase, rental, leasing, 1,639 responses). In line with the findings of other researchers, the most important arguments were the high purchase price (7.7% of responses), limited range (7.7% of responses), too frequent charging (7.3%), high battery costs (6.4%), the need to purchase a charging station for the company (6%), uncertainty about future charging costs (5.7%), charging time too long (5.6%), too few charging stations outside cities (4.9%), lack of adequate knowledge and experience (4.5%), and lack of mechanics (3.7%).

Table 2 Reasons for the lack of interest in electric vehicles

Item	Votes	Percentage
The price of the car is too high	126	7.7
The car has a limited driving range	126	7.7
Need to charge the car too often	119	7.3
High battery cost	104	6.4
Need to buy a charging station for the company	98	6.0
Uncertainty about charging costs	93	5.7
Charging time is too long	91	5.6
Very few charging stations in rural areas	80	4.9
Lack of sufficient knowledge	74	4.5
No experience with using an electric car	74	4.5
Lack of charging stations and difficulty in finding them	70	4.3
Lack of repair and service workshops	61	3.7
Less durable than a combustion vehicle in cold weather	5	3.1
Low resale value of electric cars	5	3.1
Lack of reliability (e.g., due to weather conditions)	49	3.0
Working in rural areas without electricity, I would have to take a diesel generator with me, which needs to be refueled — and that makes no sense.	46	2.8
Limited range when transporting heavy cargo	43	2.6
For our clients, it doesn't matter whether we use an electric or petrol car. So it doesn't affect our reputation.	42	2.6
If I forgot to charge my EV in the evening, and it was below zero and snowing in the morning, the car would have half power, and you'd have to drive 50 km/h. Charging takes longer; you have to wait 45 minutes at the charger. I think it's really inconvenient.	41	2.5
I don't know where at the office we could park and charge all our company cars overnight? Besides, charger prices are also high. There's a high risk of theft and fire.	38	2.3
The negative side of BEV is anxiety about loss of range on longer routes, which is a major problem.	30	1.8
Insufficient incentives from the authorities	28	1.7
I've heard stories of someone stuck in a traffic jam when it was a bit cold outside, then the car died and just stayed there.	25	1.5
We have quite heavily loaded cars and trailers, which eliminate 'optimal driving conditions', and significantly reduce the range on a single charge.	19	1.2
You have to plan completely differently if you want to use a BEV, which makes our work much harder.	18	1.1
Besides environmental benefits, cheap charging, and convenience, there are no economic benefits.	16	1.0
For diesel and petrol cars, you get the same government compensation as for electric cars. The government hasn't done enough for electric cars.	13	0.8

Item	Votes	Percentage
For most electric car problems, as a company, we have solutions, but who among us has the time for them?	**12**	**0.7**
Our biggest problem with these cars is that our employees start their workday from home. If they had a battery-electric vehicle (BEV), they would need to charge it at home, which is costly. We have quite a lot of employee turnover, so we would need to install a charging station at the home of someone who might leave our company next year.	**0**	**0**
A company car can be electric, but not a work vehicle. A work vehicle is never charged at the office and very often travels long distances. It does not make sense for us to spend time researching and pursuing an electric work vehicle, since the technology generally does not yet meet our range needs.	**0**	**0**
The problem with electric cars is planning. It takes too much time — who should handle and implement it? The issue isn't just the car's performance today. It's also an economic question — someone needs to take care of it, it takes time, and time costs money, and we don't have the time.	**0**	**0**
For small and medium-sized enterprises, the transition to electric vehicles is very difficult. SMEs have many cars (unlike micro firms) but lack the human resources to handle purchasing and later planning for EVs (large companies have more resources for this).	**0**	**0**

5   Discussion

The survey confirmed the reasons for the low interest in electric cars among micro-enterprises. The main reason was the high purchase price (7.7% of responses, Figure 22) and battery costs (6.4%, Figure 21), which pose a serious challenge for micro-entrepreneurs with limited capital and high uncertainty about future operations (which is consistent with the observations of other researchers, including [1,6].

Logistics in micro-enterprises requires reliable short-range vehicles and micro-entrepreneurs recognise the long-term cost-effectiveness of electric cars and the durability of their engines, but buy almost exclusively combustion-engine cars because they are more versatile and cheaper to purchase. Entrepreneurs are familiar with this technology, have mechanics, and do not have to spend money on charging stations and photovoltaics (this is also confirmed by [20,21]). According to the respondents, electric cars are most cost-effective when the company has its own photovoltaic installation and surplus power (consistent with the research by [9]).

On the other hand, if we look at the distance from the headquarters, where 95% of journeys are made, the vast majority of micro-enterprises cover distances shorter than the range of electric cars, and in many cases, replacing a combustion engine car with an electric one would not affect driving comfort and charging time (main charging would take place at night on the company's premises), which shows that in the case of micro-enterprises, BEV distances are sufficient for unrestricted movement.

Analysis of survey (which the authors consider to be the scientific novum introduced by this research) data showed that micro-entrepreneurs follow technological developments and price changes and are considering purchasing an electric car, if only to see for themselves the advantages and disadvantages of such a car. Whether they ultimately make a purchase seems to depend on the scale of the economic benefits they can obtain. For these companies, the present is more important than the future, given the high uncertainty about the continuation of their business in the coming years and the small scale of their operations (consistent with [24]).

Micro-enterprises were most interested in subsidies for the purchase of electric cars (see Table 1), free parking (see Figure 28), access to bus lanes (see Figure 28), tax exemptions, lower motorway tolls and access to city centres. The main factors encouraging purchase were subsidies and grants (8.5-7.0%, Table 1), as well as necessity – in large cities, combustion engine cars are often banned from city centres (12%, Figure 28). This confirms the article's hypothesis that these are the most important incentives for micro-entrepreneurs to purchase BEVs.

As for the limitations of the study, it is worth mentioning that the CAWI method encourages self-selection (response rate 0.5%), the research sample was limited to Małopolska (no generalisation to Poland), TCO was not modelled in the article, and few qualitative comments were obtained. These limitations can be overcome by conducting longitudinal tracking, using a nationwide sample, and performing an economic analysis.

6   Conclusions

Analysis of the survey results shows that micro-enterprises in Małopolska show little interest in electric vehicles (BEVs), mainly due to their high purchase price and battery costs, even though 84.4% of their routes are within the range of BEVs (Figure 7). For the above reasons, it is not surprising that the most effective incentives indicated by entrepreneurs included: subsidies (8.5%), free parking (7.5%), and bus lanes (6.5%) (Table 1). As our research shows, the length of travel routes was not the major obstacle to BEV adoption among microenterprises; instead, it was a steep initial price, which is the scientific novum this paper introduced.

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Fiscal and regulatory incentives for electric vehicle adoption in Polish micro-enterprises: economic analysis and policy recommendations
Joanna Wyrobek, Lukasz Poplawski, Marek Lesniak, Marcin Surowka, Bogusław Waclawik

From the perspective of micro-enterprises, therefore, an important measure to promote BEVs would be to extend the NaszEauto programme to all businesses and to use a prepayment system instead of refunds. In addition, micro-enterprises would expect subsidies for private rural chargers (despite the popularity of photovoltaics). The results of the study also show the need for information programmes for micro-enterprise owners and for stability in the incentive system, e.g., maintaining a uniform formula for 5 years rather than annual changes and the resulting uncertainty. In many cases, it would be sufficient to maintain free parking for BEVs and to extend access to city centres for a longer period, which is a much cheaper solution than a subsidy programme.

These changes should unlock electromobility among Polish micro-enterprises, supporting decarbonisation and the EU's Green Deal objectives.

If we look at the problem more broadly, from the perspective of the European Union as a whole, it seems that the implementation of electric cars (similar to renewable energy sources) should be in the interest of the entire European Union, and not be treated solely as an obligation and a goal for member states which, like Poland, cannot afford the incentives that entrepreneurs expect. Poland may be the 20th-largest economy in the world. However, its GDP per capita is less than half the EU average, and it cannot compete with countries such as Germany or Norway (which is not an EU member), as mentioned earlier in the article. Poland is unable to significantly increase the share of renewable energy in electricity production or increase the share of electric cars because it cannot afford to do so, either as a country or as citizens. The European Union Emissions Trading System and the Carbon Border Adjustment Mechanism raise electricity prices most for the poorest countries, further depriving them of money. This creates a vicious circle, created in the hope that the penalty system would fulfil its function. The 50% difference in GDP per capita is striking and should give pause for thought as to whether the current system is really beneficial for the EU as a whole. The near-zero investment in BEVs by a large group of entities, such as microenterprises, suggests this is a road to nowhere. The current system only exacerbates the barriers for poorer countries and poorer micro-enterprises. This shows that flexible targets are needed, adjusted to GDP/per capita and ME dominance (97% of companies). Without policies that take into account the realities of Polish micro-enterprises (capital, rural areas, PV synergy), the Green Deal targets will bypass 30% of GDP generated by micro-enterprises.

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Transformation of controlling in perspective of reengineering and modification of organizational structures in industrial enterprises
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Transformation of controlling in perspective of reengineering and modification of organizational structures in industrial enterprises

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Abstract: Organizing as a key management function appears in two basic forms, dynamic and static. The dynamic form includes the processes and activities taking place in the organization that ensure its effective functioning. The static form is represented by the organizational structure, which determines the way the organization is structured and the interrelationships between the individual components of the organization. Every organization has some type of organizational structure, which may be informal or formally established. This organizational structure determines the management and coordination of operations in the enterprise. Transformation of organizational structure should be considered when it is unable to respond to the changing conditions of the enterprise functioning. Such a transformation would help to improve the management systems of the enterprise. This paper focuses on controlling as a management support function in industrial enterprises and the reasons for its transformation. The aim of the research was to assess the need for transformation of controlling in industrial enterprises in Slovakia. The research tool used in the paper was a questionnaire, which was distributed to medium and large enterprises in Slovakia. The paper also analyses the reasons for non-transformation of controlling as well as the advantages and disadvantages of this transformation. The transformation of controlling primarily brings standardization and simplification of processes, leading to greater efficiency, cost savings, and improved team coordination. Although the transition may temporarily reduce data quality and affect decision-making, the overall benefits significantly outweigh the risks, making the company more competitive and adaptable to market challenges.

1 Introduction

Enterprises are constantly facing changes in the way they do business and implement new technologies. In addition to technological innovation, enterprises often must respond to changes in legislative requirements or customer preferences. If the existing organizational structures cannot respond to market changes, changing conditions outside but also inside the organization, it is reasonable to consider its transformation. Transformation to a more flexible structure that allows faster adaptation to change should be considered. Transforming structures often removes redundant layers of management, simplifies processes and streamlines communication between departments. Transforming organizational management structures should contribute to faster decision-making, better use of resources and the elimination of any waste. Eliminating waste is usually associated with production processes, but waste is too costly in any area, so it should also be identified in administrative processes that do not meet the requirements for modern management and faster adaptation to these changes. Therefore, in this paper we have measured the reasons for transforming controlling, as an important management support function, from the perspective of making the management of industrial enterprises more efficient.

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Zdenka Gyurak Babelova, Natalia Vranakova, Eva Santava, Milos Cambal

In today's dynamic times, controlling plays a very important role in business management. Controlling provides support in the management of the enterprise, being based on a complex information and organizational interconnection. Its main objective is to provide relevant cost information, thereby facilitating timely and correct management decision-making at all stages of the decision-making process.

The fundamental objective of any transformation is to align financing with the overall strategy of the business, thereby streamlining processes and improving the quality of service provided by the enterprise, not only to internal but also to external customers. Transforming controlling means aligning its activities and funding with the strategic objectives of the enterprise.

2   Literature review

The Controlling is an interdisciplinary management tool aimed at supporting the planning, management and control of processes in an organization. Its main areas include providing up-to-date and relevant information for decision making and efficient allocation of resources. The goal is to increase the efficiency and effectiveness of the organization through systematic coordination between planning, execution and control [1,2]. The fundamental characteristics of controlling include its universality, dynamism, and pervasiveness. It is a process that is continuous and adapts to changing conditions and objectives. Controlling also helps in preventing problems and ensures the achievement of organizational goals [3]. Modern technological innovations such as big data, artificial intelligence and cloud computing are fundamentally changing the approach to controlling.

Digitalization enables more accurate and faster data analysis, supports decision making and enables greater process automation [4]. Digital technologies provide more than just providing access to vast sources of information and knowledge; they are fundamentally changing the way industrial businesses are managed and enabling real-time collaboration across global teams [5].

However, the effectiveness of controlling in an organization is also influenced by its integration into the organizational structure, where its position and integration into decision-making processes plays a key role in achieving goals and optimizing the performance of the organization. Line organizational structures are key to clearly defining hierarchies and responsibilities in the organization, which promotes decision making and accountability [6]. The type of organizational structure has a significant impact on the successful institutionalization of processes such as product line engineering and ensures their alignment with long-term strategies [7]. Different organizational designs can influence the management of innovation and dynamic capabilities, especially in creating an environment that fosters radical innovation [8]. Linear organizational structures allow for a more adaptable framework, which is essential for organizations facing dynamic market conditions and the need for rapid response [9]. Integrating process owners within linear organizations can improve coordination and streamline operations, thereby improving overall efficiency [10]. Clear hierarchical organization in line structures promotes effective communication channels that are key to decision making and operational success [11]. The staff organizational structure combines line hierarchy with professional support positions. Staff provide advice and support to line managers without direct decision-making authority, thereby helping to meet the organization's strategic objectives. This structure allows for specialization and effective collaboration but can create conflict in authority and increase payroll costs. For optimal implementation, it is necessary to clearly define responsibilities and encourage collaboration between line employees and staff employees [12].

Changes in organizational structures are driven by factors such as improving organizational performance and design, adapting to external changes, and technological advances. These aspects indicate the necessity for organizations to adapt in order to respond to internal and external challenges, thereby maintaining efficiency and competitiveness.

Effective organizational design is critical for determining performance and facilitating collaboration among organizational members, which requires a scientific and empirical approach to design. The relationship between task allocation and coordination mechanisms is essential because interdependent and uncertain tasks require a well-structured design to function effectively [13]. Organizations must respond to a complex, dynamic environment characterized by globalization and competitive pressures, which requires agility in their structures [14]. Changes in organizational structure and processes are often driven by the adoption of new technologies, which can change the roles and responsibilities of employees [15]. The acceptance and integration of artificial intelligence (AI) within organizations is influenced by both individual and organizational factors, highlighting the importance of being prepared for technological change [16].

Lean methods enable enterprises to streamline various processes such as production, logistics or administration, while their application can also lead to optimization of the organizational structure. Through the identification and elimination of waste, better coordination and higher productivity of teams are ensured. Lean manufacturing practices and supply chain integration together enhance supply chain agility, which positively affects operational performance [17]. The integration of lean principles into logistics processes facilitates a smoother flow of materials and information across the supply chain, thereby improving overall efficiency [18], while also contributing to significant reductions in transportation costs and waste, as demonstrated in various case studies [19]. In this way, the enterprise not only adapts to dynamic market conditions, but also strengthens its competitive advantage.

The optimization of the different activity levels is illustrated in Figure 1.

Value-added activities: any activity that absorbs materials or information and converts or transforms them in a way that meets customer needs and for which the customer is willing to pay.
OPTIMIZE!
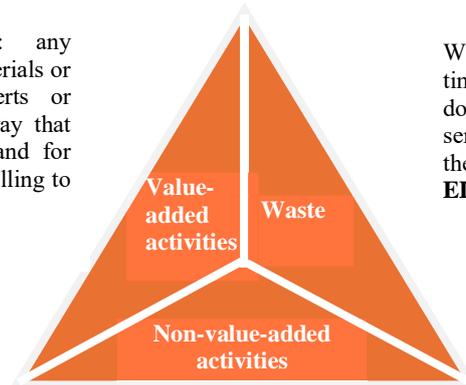
Waste: activities, processes, time, materials, space, etc. that do not add value to a product or service and are not necessary for the system or process.
ELIMINATE!

Non-value-added activities: any activity that is necessary given the system or processes in use today, but that does not contribute any value to the product or service or to customer satisfaction.
REDUCE!

Utilization of potential at the activity level increases efficiency.

Figure 1 Optimization of the different activity levels (adapted from [20])

The Business processes are the focus of lean administration, because these are the ones that need to be optimized. Before anything can be improved, it must first be understood in detail. That's why analysis is the first step of transformation. Such an analysis records the overall process in detail, examining, naming and measuring each step of the process. At the same time, the activities are categorized because three types of activities can be identified at each level [20]:

- Value-added activities - activities that work for the benefit of customers. Material or information is processed in such a way that added value is created for the customer and the customer is willing to pay for this value.

- Non-value-adding activities - activities that do not directly contribute to customer satisfaction but are necessary as preparation or continuation.

- Redundant activities - activities that require a certain amount of material, space or time without contributing in any way to the creation of value and certainly without being requested by the customer.

Optimization of individual activity levels illustrates how to achieve process improvements and how to identify necessary actions.

The goal of lean administration consists of creating a system for the efficient organization of processes in administration that contributes to satisfying a need and value for the customer but does not directly contribute to the creation of added value. Every organization must have administrative process support in order to be able to produce products or provide services, but no customer pays for administrative process support [21].

The need to change organizational structures stems from a combination of demands on organizational performance and design, adaptation to external change, and technological development. Together, these factors highlight the importance of a flexible and efficient organization that can successfully face the challenges and complexities of the modern business environment.

A business in a market economy is under great pressure from competition. Rising costs, unstable economic situation, predatory competitive environment on the domestic and foreign market, etc. are the reasons why the management of the enterprise is constantly improving its management systems. It responds to new situations with new management functions that would allow to evaluate the fulfilment of planned enterprise objectives, to detect risks, to draw attention to real deviations from the desired development, to analyse and evaluate the effects of business activities and decisions, to plan and program the development of the enterprise, to inspire the management of the enterprise to reveal new business activities bringing economic effect [22]. By optimizing processes in the enterprise, the input required to perform the services will be significantly reduced. This will reduce operating costs and increase business competitiveness.

3 Methodology

The importance of assessing the need for transformation of controlling in industrial enterprises in Slovakia lies in its ability to reflect the dynamic changes in the business environment. Such an assessment helps to identify how controlling can better support strategic decision-making, optimize processes and ensure effective resource management. At the same

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time, it allows to adapt to new technological trends and market requirements, thereby increasing the competitiveness of enterprises.

The main objective of the presented research was to evaluate the need for transformation of controlling in organizational structures in industrial enterprises based in Slovakia. To meet the main objective, we set the following research questions:

RQ1: If the transformation of controlling has not taken place in industrial enterprises yet, what are the reasons?

RQ2: What changes would the implementation of controlling transformation in industrial enterprises bring?

RQ3: How do experts from industrial enterprises evaluate the benefits of implementing controlling transformation?

RQ4: How do experts from industrial enterprises evaluate the disadvantages of implementing controlling transformation?

The questionnaire was designed for data collection and distributed online via Google Forms platform. The data collection took place between October 2022 and January 2023. The research sample consisted of medium and large enterprises with more than 50 employees, operating in manufacturing industries and based in Slovakia. According to the set criteria, the sample size was determined to be 150 industrial enterprises.

To calculate the minimum required sample size, we used the minimum sample calculation methodology [23], setting the confidence level at 95% and the margin of error at 10%. Based on these parameters, the minimum required sample size was set at 59 enterprises.

The sample was determined without repetition based on the responses from the questionnaire survey. Out of a total of 150 active enterprises contacted, selected according to the above criteria, 61 respondents replied. This number therefore meets the minimum size requirement, and the sample can thus be considered representative. The overall return rate in the questionnaire survey is 40.7% in relative terms. Using descriptive statistics, the responses to the individual questions of the questionnaire are interpreted by tables and graphs of frequency distribution. The structure of the research sample is shown in Table 1.

Table 1 Characteristics of the research sample

INDUSTRY	MAJORITY OWNER	THE SIZE OF ORGANIZATION IN TERMS OF NUMBER OF EMPLOYEES		
		Medium-sized organization (50 – 249 employees)	Large organization (over 250 employees)	Total
		Count	Count	Count
AUTOMOTIVE	Foreign	5	16	21
ELECTROTECHNICAL	Foreign	1	14	15
METALLURGICAL	Foreign	1	0	1
CHEMICAL	Slovak	1	0	1
OTHER	Slovak	0	1	1
	Foreign	2	3	5
MECHANICAL ENGINEERING	Foreign	6	11	17
TOTAL	Slovak	1	1	2
	Foreign	15	44	59

Table 1 provides an overview of enterprises according to their size, distinguishing between medium-sized enterprises (50-249 employees) and large enterprises (over 250 employees). It also categorizes enterprises by industry and type of majority owner (Slovak or foreign).

The survey covered enterprises as follows: there are 21 enterprises in the automotive industry, of which 5 are medium-sized and 16 are large, all of which have a foreign owner. The electrical industry comprises 15 enterprises with foreign ownership, of which 1 medium-sized and 14 large. The metallurgical industry has only 1 medium-sized enterprise with foreign ownership. The chemical industry represents 1 medium-sized enterprise with Slovak ownership. Another category includes other industries, where 6 enterprises are classified: 1 large enterprise with Slovak ownership, 3 large enterprises with foreign ownership and 2 medium-sized enterprises with foreign ownership. The mechanical engineering industry comprises 17 foreign-owned enterprises, of which 6 are medium-sized and 11 large.

In total, the survey covered 2 Slovak-owned and 59 foreign-owned enterprises, of which 15 are medium-sized enterprises and 44 are large enterprises. As the research showed, controlling is implemented mainly in foreign, medium and large enterprises. In the questionnaire survey, up to 73.8% of enterprises are large enterprises and only 26.2% are medium-sized enterprises. The results of the research were subsequently processed in MS Excel and IBM SPSS software in the form of graphs, cross-tabulations of frequencies and descriptive statistics.

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4 Results

In the following analysis, we focused on whether a separate controlling department provides controlling in the analysed enterprises. Only 8.2% of enterprise representatives (2 large enterprises and 3 medium-sized enterprises) answered that they did not have their own controlling department. As even in some medium-sized enterprises there is no separate controlling department included in the organizational structure, controlling is performed by one of the members of the management as a secondary task. In this case, however, the controller can only deal with ad hoc analyses that do not have a high added value from a business management perspective.

The distribution of respondents in terms of the need to change the integration of the controlling department within the organizational structure of the enterprise and the progress transformation of controlling is depicted in Table 2.

Table 2 Cross tabulation of frequencies - the need for change in the organizational structure and the progress of transformation of controlling

		Do you consider it necessary to make a change in the organizational structure of the organization regarding the position of controlling, given the ongoing transformation of controlling?		Total
		Yes	No	
Is/Was a controlling transformation completed in	yes	1	2	3
your organization?	no	14	44	58
Total		15	46	61

It can be concluded from Table 2 that up to 46 respondents do not need to make a change in the organizational structure of the enterprises. We conclude that these were respondents from enterprises in which the organizational integration of the controlling department is line. Since the controller is integrated at the same level as other members of management, they do not need to change the organizational structure. We conclude that in the remaining 15 enterprises, where the controller is not authorized to make decisions and give orders and is directly subordinate to the enterprise management, the enterprise management does not agree with such organizational integration. Respondents largely answered that they did not undergo a transformation of controlling.

We then proceeded to evaluate the first research question.

RQ1: If the transformation of controlling has not taken place in industrial enterprises yet, what are the reasons?

The evaluation of the responses from the respondents as to why in their opinion the transformation of controlling has not taken place is shown in Figure 2.
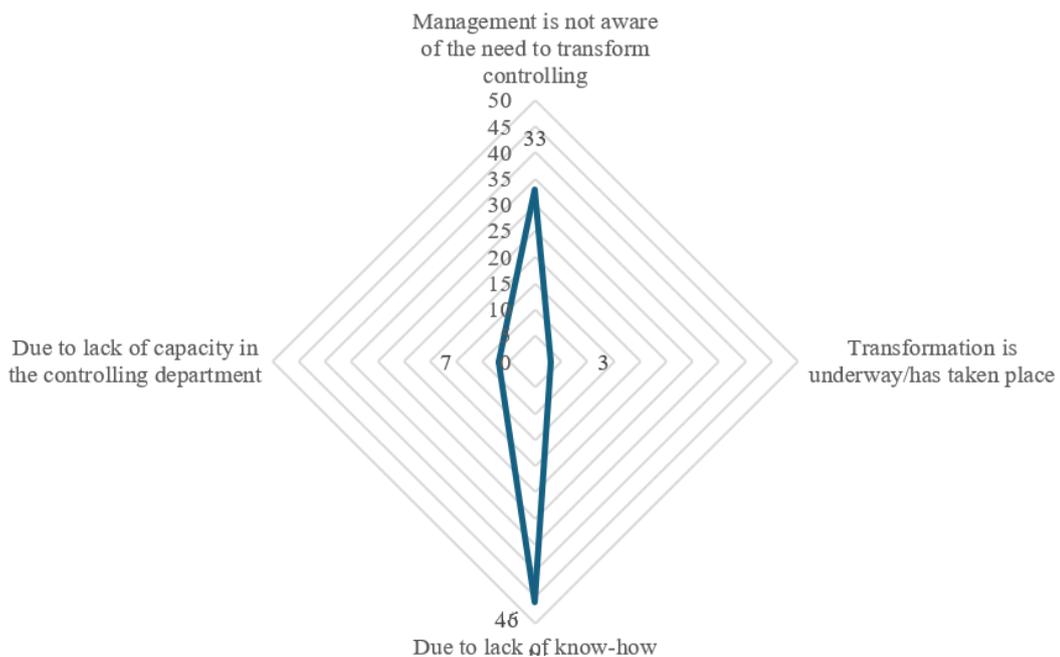
Figure 2 Reasons for not implementing transformation of controlling

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As can be seen in Figure 2, the major reason why the transformation of controlling in the enterprise is not taking place was identified by respondents as a lack of know-how.

As many as 46 respondents from enterprises answered that the main reason why the transformation of controlling has not yet taken place is due to the lack of "know-how". Another reason is that the management is not aware of the need for the transformation of controlling, which is confirmed by 33 responses from enterprises. We conclude that both reasons are related, as a total of 28 respondents chose both options. If the management of the enterprise does not have the necessary "know-how", it is not aware of the need for the transformation of controlling.

We further proceeded to evaluate the second research question.

RQ2: What changes would the implementation of controlling transformation in industrial enterprises bring?

The proportion of changes that the transformation of controlling is expected to bring to the enterprise is shown in Figure 3.
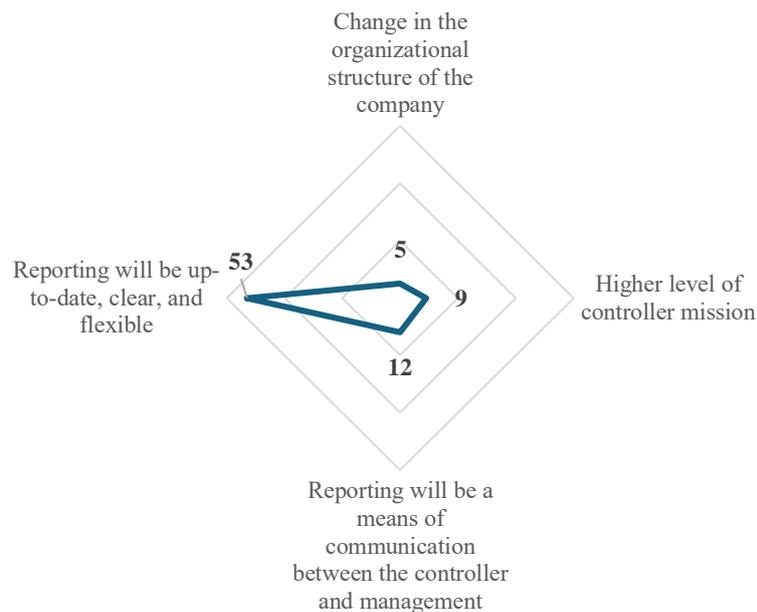
Figure 3 Changes expected by the transformation of controlling

Figure 3 shows four main areas of change, with each area represented by values that express the number of responses from respondents.

The largest number of responses, 53, concerned the expectation that reporting would become up-to-date, clear and flexible. The second most frequently mentioned change was that reporting would serve as a communication tool between the controller and management, which was reported by 12 respondents. Nine responses concerned the expectation that the transformation would increase the level of the controller's mission. Only five respondents, expect the transformation to cause a change in the organizational structure of the enterprise. The graph in Figure 3 clearly highlights that the main priority is the modernization of reporting, while the other expected changes are perceived as less significant.

We further evaluated the third research question.

RQ3: How do experts from industrial enterprises evaluate the benefits of implementing controlling transformation?

The respondents' responses on the benefits they expect the controlling transformation to bring are shown in Table 3.

Table 3 contains descriptive statistics regarding the evaluation of the six benefits of the controlling process transformation. Respondents were asked to number the benefits from 1 (most relevant benefit) to 6 (least relevant benefit) according to their perspective. Statistics include minimum and maximum ratings, average rating (Mean) and standard deviation (Std. Deviation) for each benefit.

The results in Table 3, regarding the benefits of controlling transformation show the following:

Elimination of controlling processes: The average rating was 3.21 with a relatively high standard deviation of 1.654, indicating that respondents had different opinions on this benefit. Standardization of controlling processes: It was rated as the most relevant benefit with an average score of 1.92 and the lowest standard deviation of 1.038, indicating greater agreement among respondents.

Simplification of controlling processes: The average rating was 2.56 with a relatively low standard deviation of 0.847, indicating relatively high agreement among respondents. Automation of controlling processes: The average rating was 3.00 with a standard deviation of 1.211.

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Reduction of process hours: This benefit was rated as less relevant, with a mean score of 4.82 and a low standard deviation of 0.827.

Savings in personnel costs: It was rated as the least relevant benefit with a mean score of 5.49 and a standard deviation of 1.233.

A total of 61 respondents responded to all questions. The data indicate that standardization and simplification of controlling processes are perceived as the most important benefits, while savings in personnel costs and reduction of process hours are perceived as the least important.

We then evaluated the fourth research question.

RQ4: How do experts from industrial enterprises evaluate the disadvantages of implementing controlling transformation?

A representation of the disadvantages (1 being the biggest disadvantage, 4 being the smallest disadvantage) that respondents expect the controlling transformation to bring is shown in Table 4.

Table 3 Benefits of the controlling transformation

DESCRIPTIVE STATISTICS					
	N	Minimum	Maximum	Mean	Std. Deviation
Elimination of controlling processes	61	1	6	3.21	1.654
Standardization of controlling processes	61	1	5	1.92	1.038
Simplification of controlling processes	61	1	6	2.56	0.847
Automation of controlling processes	61	1	6	3.00	1.211
Reduction in process hours	61	2	6	4.82	0.827
Savings in personnel costs	61	1	6	5.49	1.233

Table 4 Disadvantages of the controlling transformation

DESCRIPTIVE STATISTICS					
	N	Minimum	Maximum	Mean	Std. Deviation
Reduction in the quality of controlling data	61	1	4	1.28	0.609
Reducing the number of key performance indicators	61	1	4	2.38	0.799
Reduction in the number of employees	61	1	4	3.08	0.737
Loss of motivation of current controlling employees	61	1	4	3.26	1.031
Valid n (listwise)	61				

Table 4 shows the average ratings of the individual disadvantages, along with the minimum and maximum ratings and standard deviations.

The reduction in the quality of controlling data was rated as the biggest disadvantage, with an average score of 1.28. Low standard deviation (0.609) indicates a high level of agreement among respondents.

The reduction in the number of key performance indicators was perceived as the second most significant disadvantage, with an average rating of 2.38 and a slightly higher standard deviation of 0.799.

The reduction in the number of employees achieved an average rating of 3.08, indicating that it is perceived as a less significant disadvantage. The standard deviation (0.737) indicates a relative agreement among respondents.

The loss of motivation of current controlling employees was rated as the least significant disadvantage, with an average score of 3.26. The standard deviation (1.031) indicates a greater spread in the ratings, which may signal a diversity of opinions among respondents. Overall, respondents agreed that the reduction in the quality of controlling data represents the greatest disadvantage of the transformation, while loss of employee motivation is perceived as the least significant.

5   Discussion

Process transformation can significantly contribute to improving the efficiency of an enterprise through precise modelling and reengineering of business processes, which are key tools for organizational transformation. Implementing these changes allows an enterprise to optimize performance and respond flexibly to market challenges. Within the framework of controlling, this transformation plays a key role in improving management processes, which helps managers

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maintain competitiveness and achieve significant improvements in results through continuous optimization of processes and their better connection with the goals of the organization.

Business process modelling provides a structured approach to analysing and improving the efficiency and effectiveness of business processes, which leads to cost savings and increased performance [24]. Their comprehensive understanding through modelling allows organizations to effectively integrate and analyse their operations, which is crucial for achieving business goals [25]. Business process reengineering is a critical method for transforming inefficient processes, allowing organizations to redesign their operations to achieve dramatic performance improvements [26], and can lead to significant organizational transformation by enabling the redesign or replacement of outdated processes, thereby increasing overall productivity [27].

Continuous analysis and optimization of business processes are essential for maintaining competitive advantage, as they enable organizations to adapt to a changing environment and improve key performance indicators [28]. Effective management encompasses the full cycle of planning, implementation, monitoring, and improvement, ensuring that processes remain effective and aligned with organizational goals [26].

The main reasons why business process transformation does not take place are related to several key factors that highlight the complexity and difficulty of implementing effective business process management and reengineering. These factors reflect organizational barriers, insufficient know-how, and resistance to change, which create significant challenges for successful transformation. Many business process management initiatives fail due to lack of alignment with corporate change strategies, suggesting that workflow redesign does not automatically lead to effective organizational change [29]. A structured framework for managing organizational change during workflow redesign is often lacking, which can lead to misalignment and subsequent failure of business process management implementation [30]. Projects that use a one-size-fits-all approach are prone to failure because they do not adequately consider the specific situational requirements of different business contexts [31].

The benefits of business process transformation include improving efficiency through process optimization, ensuring high quality modelling, and effectively utilizing reengineering. Together, these factors lead to increased organizational performance and enhanced competitive advantage. Continuous analysis and optimization of business processes are essential to turn them into competitive advantages for enterprises and are key to guiding organizations in improving processes according to specific characteristics [32]. Business process reengineering serves as a tool for transforming inefficient processes, allowing for either redesign or replacement to achieve significant performance improvements. Case studies show that reengineering can be used across industries to increase overall productivity and service quality [27].

The main disadvantages of business process transformation include the complexity and opacity of process modelling, methodological challenges in implementing improvements, and potential resistance to change from employees. These factors can significantly limit the effectiveness of transformation activities, which means that it is important for organizations to address these challenges proactively and in a planned manner to ensure successful implementation of change. Many business process improvement approaches do not adequately describe the act of improvement itself, which can hinder effective transformation [33]. Implementing digital transformation initiatives can be particularly challenging in bureaucratic environments where existing processes may resist change due to their complexity [34]. Organizations can face significant barriers in managing the cultural and operational changes required for successful business process transformation, leading to potential resistance from stakeholders [35]. Transformation will only be successful if the consent to support the decision or change is obtained from the beginning from all the employees involved. It is the employees who know all the processes in the enterprise, probably better than any manager. Employees often make the most effective suggestions for improvement. And ultimately, they will have to implement all the required changes. Motivating employees to accept the changes and fully use their potential is important, which is important for all phases of business process optimization.

When an enterprise's management starts optimizing processes, it makes many unexpected discoveries during the optimization process, identifying and solving problems that it did not even know it had. It is necessary to reorganize not only the activities of individual employees or departments, but also, more importantly, their interfaces. Interfaces are weak points in business processes. These interfaces can only be effectively improved if they are precisely defined. Efficient information processing means that the required information is delivered to the required place at the required time. Just-in-time service provision in an enterprise is only achieved if the individual process interfaces, i.e. the required data, information and documents, are described so precisely that the enterprise's employees know exactly what to do. Once clearly defined routines have been developed, after a short period of time all activities can be performed as part of the same flow and delivered just in time [20].

6 Conclusion

The transformation of controlling is essential for industrial enterprises that are trying to respond effectively to dynamic changes in the business environment. The main reason is the need to modernize processes in order to improve the quality of management and strategic decision-making. Specific forms of organizational structures, especially staff structures,

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require change, as they often lead to inefficiency in management, conflicts of competence and excessive bureaucracy, which hinder flexibility and innovation.

One of the most important aspects of the transformation of controlling is the modernization of reporting, which becomes up-to-date, flexible and better adapted to the needs of management. Reporting is a key tool for providing information on the performance of the enterprise, and its optimization can significantly increase the quality of decision-making processes.

The main obstacle to implementing the controlling transformation is the lack of know-how and low awareness of its need of management. This deficit can lead to overlooking the potential of controlling as a strategic tool, which represents a serious deficiency in business management.

The greatest advantage of the controlling transformation is the standardization and simplification of controlling processes, which can bring higher efficiency, cost reduction and better coordination of teams. On the other hand, the disadvantage is the possible reduction in the quality of controlling data, especially during the transition period, which can lead to erroneous decisions and losses in business management.

Overall, however, the advantages that the controlling transformation brings significantly outweigh its disadvantages. If an enterprise can overcome the aforementioned obstacles, it gains a powerful tool for increasing its competitiveness and ability to adapt to the challenges of the modern market.

The theoretical contribution of the article lies in emphasizing the need for controlling transformation as a tool for increasing the efficiency of enterprises. The text expands theoretical knowledge on the impact of organizational structures, especially staff structures, on process modernization and identifies reporting as a key element of flexible management. Identification of barriers, such as lack of know-how and managerial awareness, reveals factors of change failure. The importance of transformation is also shown in the standardization and simplification of processes, which provides theoretical foundations for a better understanding of its impacts on organizations.

The practical benefit for industrial enterprises lies in the possibility of increasing efficiency through the transformation of controlling, which brings process standardization and simplification of management. For managers, this means better transparency and flexibility in reporting, which facilitates decision-making and rapid adaptation to changes in the business environment. In addition, the identification of barriers such as lack of know-how draws managers' attention to the need for education and strategic planning to support successful changes and increase the competitiveness of their enterprises. Future research can examine how the transformation of controlling affects different types of organizational structures, especially staff organizational structures, which require adaptation to modern management processes and improved flexibility. At the same time, it is necessary to analyse how new reporting tools can support management efficiency in different industrial sectors. Attention should also be paid to the design of strategies to address barriers such as lack of know-how to ensure the smooth integration of innovations in the field of controlling.

Limitations of the research may include limited data on industrial enterprises in Slovakia, which may affect the generalizability of the conclusions. Another limitation is the focus on specific types of organizational structures, which does not take into account the specifics of other models. The lack of knowledge about the practical application of modern reporting tools or the analysis of their long-term impacts may also limit the depth of the results. These limitations indicate the need for broader and more comprehensive research.

Acknowledgement

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Unlocking the potential of logistics service quality: insights into customer satisfaction and loyalty via an extended SERVQUAL approach
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Unlocking the potential of logistics service quality: insights into customer satisfaction and loyalty via an extended SERVQUAL approach

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Abstract: The rise of e-commerce has intensified the demand for logistics services, emphasizing the need for research on service quality to enhance efficiency and customer satisfaction, ultimately fostering loyalty. This study explores the impact of Logistics Service Quality (LSQ) on customer satisfaction and loyalty in the dynamic logistics market of Ho Chi Minh City, Vietnam. Employing an extended SERVQUAL model, this study investigates six dimensions of Logistics Service Quality (LSQ): tangibility, reliability, responsiveness, assurance, empathy, and the newly added dimension of fairness, thereby providing a more comprehensive and nuanced understanding of logistics service quality. A quantitative approach was employed, analyzing data from 409 logistics service users using Partial Least Squares Structural Equation Modelling (PLS-SEM). The findings indicate that all the service quality dimensions positively influence customer satisfaction, except for reliability, suggesting a potential misalignment between customer expectations and the consistency of service performance in this market. Additionally, customer satisfaction was found to be a strong and positive predictor of customer loyalty. These results provide practical insights for logistics providers to prioritize service attributes that most effectively enhance customer satisfaction and loyalty. The study contributes to the literature by validating an extended LSQ model in a key Southeast Asian context and offers a managerial framework for improving customer relationships and sustaining a competitive advantage. This research is highly relevant for both scholars and practitioners in logistics, offering a solid empirical foundation for improving service quality and fostering customer loyalty in the sector.

1   Introduction

In today's highly competitive business environment, the management of critical logistics flows plays a pivotal role in shaping customer experiences and fostering long-term business relationships. The ability to ensure the efficient, reliable, and transparent flow of goods is no longer just a source of cost savings but a fundamental driver of competitive advantage. As the marketplace becomes more saturated, logistics service providers can no longer compete solely on price. Instead, the quality of the service delivered - termed Logistics Service Quality (LSQ) - has emerged as a key differentiator, directly shaping customer perceptions, influencing purchasing decisions, and ultimately determining a firm's long-term success. This dynamic is particularly pronounced in Vietnam, where accession to the World Trade Organization (WTO) has intensified market pressures by introducing global industry leaders such as DHL, UPS, and FedEx. This environment necessitates that domestic firms strategically prioritize and enhance their service quality to contend effectively and satisfy the escalating demands of customers in the digital era.

In Vietnam's dynamic economy, HoChiMinh City (HCMC) has emerged as a critical hub for logistics activities. Approximately 70% of these enterprises are concentrated in HCMC and its neighboring provinces. Despite HCMC's significance in the logistics sector, most Vietnamese logistics firms remain small and possess limited capital. Furthermore, deficiencies in the city's transportation infrastructure exacerbate freight congestion and elevate business logistics expenses. Although road transport is predominant in the southern region, inadequate highway infrastructure leads to

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frequent congestion, increasing labor and material costs. Logistics businesses must enhance service quality to meet customer demands in this context. Murfield et al. [1] have demonstrated that high-quality logistics services lead to customer satisfaction, which in turn fosters customer loyalty towards the logistics company. Furthermore, customer satisfaction positively influences loyalty toward products and services [2]. Consequently, loyal customers are more likely to recommend the logistics company to others. Enhancing service quality thus provides logistics companies with significant benefits, including increased revenue and market share [1].

Research on customer satisfaction with logistics service quality has predominantly concentrated on various factors such as responsiveness, exemplified by metrics like order fulfillment time [3] and order processing time [4]. Additionally, brand image has been identified as a critical determinant in evaluating logistics service quality [5]. Operational and technical service quality are also recognized as essential components within this context. However, there is no consensus on the attributes of Logistics Service Quality. The SERVQUAL model recommended by Parasuraman et al. (1988) [6], with its five core dimensions of "tangibility", "reliability", "responsiveness", "assurance", and "empathy", has traditionally been the dominant framework for assessing service quality. However, its universal applicability has been questioned, with scholars arguing for context-specific adaptations. The unique nature of the logistics industry, which involves the physical handling, storage, and timely delivery of tangible goods, suggests that additional dimensions may be necessary to fully capture the customer's experience. Furthermore, the dynamics of service quality perception can vary significantly across different economic and cultural contexts. The rapidly growing and highly competitive market of Vietnam, particularly in a major economic hub like Ho Chi Minh City, presents a compelling yet under-researched setting for examining these relationships. This study aims to investigate the effects of logistics service quality on customer satisfaction and loyalty in Ho Chi Minh City by developing and empirically testing an extended SERVQUAL model, which incorporates the dimension of "fairness" as an additional factor alongside the traditional dimensions. The inclusion of fairness is especially relevant given the increasing emphasis on ethical practices, equitable treatment, and transparency in service delivery, particularly in competitive markets. By introducing this new dimension, the study aims to provide a more comprehensive understanding of logistics service quality that better aligns with customer satisfaction and loyalty.

2 Literature review and hypothesis development
2.1 Logistics Service Quality

Though the concept of Logistics Service Quality (LSQ) has been adapted to cater to the unique needs of the logistics industry, its foundations lie in the well-established principles of service quality [5,7]. Coyle et al. [8] identified seven key criteria to assess the quality of logistics services: delivering the right amount of product, in the appropriate quantities, at the right moment, at the designated location, in proper condition, with accurate information provided to the customer, and all at a fair price [9]. This framework was further expanded upon by Rafid et al. [9], who defined logistics quality measurement as a set of attributes including timeliness, accuracy, and conditions of the service process, supply of high-quality information to clients, availability, and service provider capacity. Notwithstanding the availability of frameworks tailored specifically for logistics, a prevalent trend in quantitative research is the application of the classical SERVQUAL model. This reliance on a generic instrument highlights the potential inefficiency of using a one-size-fits-all approach to measure the distinct attributes of logistics service quality [10].

The service quality dimensions in SERVQUAL, which include tangibility, reliability, responsiveness, assurance, and empathy, can indeed be applied to the logistics industry. However, researchers have emphasized the need for developing a more comprehensive LSQ model that incorporates the nuances of the logistics domain. A key dimension highlighted in the logistics service quality literature is the fairness of logistics service providers. Customers also expect to be treated fairly in their interactions with service providers.

Tangibles

It is outlined by Parasuraman et al. (1988) [6] and encompasses aspects such as physical facilities, decor, and the appearance of personnel. This tangible dimension has been found to significantly impact customer satisfaction, as individuals tend to evaluate service quality based on these readily observable elements. Building upon this foundational research, recent studies have underscored the pivotal role of tangibility in shaping customer satisfaction, with evidence suggesting that enhancing the convenience and safety experienced by clients can have a positive ripple effect on a company's reputation and market standing [11]. As a result, the first hypothesis is formulated as follows:

H1: Tangibles have a positive influence on customer satisfaction.

Fairness

When customers perceive unfair treatment, it significantly impacts their emotions. Service failures linked to fairness issues elicit stronger customer responses than those unrelated to fairness [12]. This research also highlights the crucial role of fairness in influencing customer satisfaction, a viewpoint supported by previous studies that consistently demonstrate the strong connection between fairness and customer satisfaction [13]. Therefore, the second hypothesis is formed as follows:

H2: Fairness has a positive influence on customer satisfaction.

Reliability

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When assessing service quality, individuals typically evaluate the reliability of enterprises by their ability to deliver services accurately and punctually as promised. Numerous studies have shown that reliability significantly impacts customer satisfaction [14]. In a study focusing on minicab taxi services in Ghana, reliability emerged as a critical component of customer satisfaction [15]. When consumer perceptions regarding the reliability of companies are favorable, it leads to positive outcomes in terms of customer satisfaction. Therefore, the third hypothesis posits:

H3: Reliability has a positive influence on customer satisfaction.

Responsiveness

According to Munusamy et al. (2010) [16], responsiveness pertains to the staff's ability to effectively address clients' issues, including both the speed and willingness of the workforce to assist without prompting, thereby significantly impacting customer satisfaction [17]. Additionally, other studies highlight responsiveness as a crucial factor in enhancing customer satisfaction [18]. Moreover, clients expect prompt responses from companies, and their satisfaction is prone to significant negative effects if they receive poor treatment or lack attention from staff [11]. Therefore, the fourth hypothesis is proposed as follows:

H4: Responsiveness has a positive influence on customer satisfaction.

Assurance

This dimension relates to the services' accuracy, which must align with the company's claims without any alterations. Furthermore, Furuhata et al. [19] highlighted assurance as a crucial factor in ride-sharing services. Additionally, research conducted by Rust et al. [20] suggested that security and privacy concerns are significant factors in customer satisfaction. Therefore, the fifth hypothesis is as follows:

H5: Assurance has a positive influence on customer satisfaction.

Empathy

In the competitive landscape of the same industry, companies strive to secure market dominance. To achieve this, many firms research customer empathy, aiming to develop tailored services that assist clients in their tasks and consistently integrate into their overall workflow [21]. A study conducted in the Indian online cab industry revealed that empathy significantly enhances customer satisfaction [22]. Consequently, we propose the following hypothesis:

H6: Empathy has a positive influence on customer satisfaction.

2.2 Customer satisfaction and customer loyalty

Customer satisfaction and loyalty are critical indicators of long-term business success. Research has consistently demonstrated a strong positive influence of customer satisfaction on loyalty, ultimately leading to overall business growth. Several studies have highlighted customer loyalty as a key foundation for profitability [23]. This positive relationship between satisfaction and loyalty has been empirically supported by numerous studies [24]. The positive link between satisfaction and loyalty has been confirmed by various studies [25,26]. Based on this established body of research, the following hypothesis (H7) is proposed (Figure 1):

H7: Customer satisfaction has a positive influence on customer loyalty.

The preceding literature review synthesizes a broad and diverse body of international research, establishing a clear scholarly consensus on the critical relationship between logistics service quality, customer satisfaction, and loyalty. This established foundation not only underscores the significance of the topic but also provides a robust theoretical justification for the hypotheses guiding this study.

Figure 1 The proposed research model

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3 Methodology

This study employs a quantitative approach using PLS-SEM (Partial Least Squares Structural Equation Modelling. The questionnaire, divided into three sections, first informed participants of the study's academic purpose and guaranteed anonymity of responses. The second section explored demographic characteristics, gathering information on gender, age, occupation, income, and frequency of logistics service usage. Finally, the third section assessed respondents' perceptions regarding logistics service quality in HCMC. The questionnaire used a five-point Likert scale ranging from "strongly disagree" (1) to "strongly agree" (5) to measure the dimensions of logistics service quality, customer satisfaction, and consumer loyalty (Table1).

Table 1 Measurement scale

Construct	Measurement items	Sources
Tangibles (TA)	TAI: "The logistics service provider has modern-looking equipment."	[10,27]
	TA2: "The logistics service provider has a visually attractive interior."	
	TA3: "The logistics service provider has modern facilities."	
	TA4: "The employees of the logistics service provider always look neat."	
	TA5: "The materials connected with the services are visually attractive."	
Fairness (FA)	FA1: "The employees of the logistics service provider treat me with an unbiased attitude."	[28]
	FA2: "The employees of the logistics service provider produce desired results for all customers without bias of any kind."	
	FA3: "The employees of the logistics service provider deliver good outcomes for all customers regardless of who they are."	
	FA4: "The employees of the logistics service provider help all customers get the outcomes they need without favoring any one group."	
	FA5: "The activities of the employees of the logistics service provider are conducted without bias."	
Reliability (RE)	RE1: "When the logistics service provider promises to do something within a certain period of time, it fulfils the promise."	[10,27]
	RE2: "When a user has a problem, the logistics service provider shows a sincere interest in solving the problem."	
	RE3: "The logistics service provider provides adequate services from the first time onwards."	
	RE4: "The logistics service provider will provide the services at the time it promises to do so."	
	RE5: "The logistics service provider insists on flawless service."	
Responsiveness (RES)	RES1: "The logistics service provider always informs the customers about the exact time when the service will be performed."	[10]
	RES2: "The logistics service provider responds to unexpected/ urgent orders."	
	RES3: "The employees of the logistics service provider will provide prompt service to the customers."	
	RES4: "The employees of the logistics service provider will be ready to help the users at any time."	
	RES5: "The employees of the logistics service provider will never be too busy to answer the requests of the customers."	
Assurance (AS)	AS1: "The behaviour of the employees of the logistics service provider instils confidence in the customers."	[27]
	AS2: "The clients feel secure in the business operations with the logistics service provider."	
	AS3: "The employees of the logistics service provider are always polite to the customers."	
	AS4: "The employees of the logistics service provider have the knowledge to answer the questions of the customers."	
Empathy (EM)	EMI: "The logistics service provider devotes individual attention to every user"	[27]
	EM2: "The employees of the logistics service provider devote personal attention to customers."	
	EM3: "The logistics service provider will focus its attention on what is best for the customers."	
	EM4: "The employees of the logistics service provider understand the specific needs of the customers."	
	EM5: "The business hours of the logistics service provider suit the needs of all customers."	
Customer Satisfaction (CS)	CS1: "I am satisfied with the overall service quality of the logistics service providers."	[29]
	CS2: "I am satisfied with the processes or operations of the logistics service provider."	
	CS3: "I am satisfied with the facilities and physical infrastructure of the logistics service provider."	
	CS4: "I am satisfied with the management and employees of the logistics service providers."	
	CS5: "I am delighted with our relationship with the logistics service provider."	
Customer Loyalty (CL)	CL1: "I am committed to the relationship with the logistics service provider."	[2,29]
	CL2: "I will likely recommend the logistics service provider to others."	
	CL3: "I will continue the relationship with the logistics service provider as long as possible."	
	CL4: "I consider this logistics service supplier my first choice to use these services."	
	CL5: "If all the other attributes are similar (price, service, quality, ...), I will always use the logistics services provided by the supplier."	

An initial online pilot survey was conducted from October to November 2024 to assess the feasibility of the questionnaire. The survey was directly distributed to 50 respondents via email, communication apps (such as Zalo, Viber, and Messenger), and online interviews. The results indicated that all participants comprehended the questions. Then, the official questionnaire was distributed from November to December 2024. A total of 450 questionnaires were collected, out of which 409 were valid, resulting in a response rate of 90.89%. The questionnaire was distributed through email and communication applications to facilitate data collection.

4 Results and discussion

4.1 Respondents' profiles

As seen in Table 2, the survey participants were nearly equally divided by gender, with 48.41% female and 51.59% male. The largest age group of respondents was 18-30 years old, making up 67.72% of the sample. The remaining respondents were divided between 31-40 years old (18.58%) and those 41 or older (13.69%). Students represent the largest occupational segment at 42.79%, followed by office staff and businessmen at 28.36% and 15.16% respectively. The income distribution reveals a significant proportion of respondents earning less than 5 million VND, accounting for 32.03%. Regarding logistics service usage frequency, the majority, at 36.92%, utilize the service between 2 to 4 times, indicating a regular engagement with the service provided.

Table 2 Profile of survey respondents

Characteristics	Observations	Frequency n = 409	Percentage
Gender	Female	198	48.41%
	Male	211	51.59%
Age	18-30 years old	277	67.73%
	31-40 years old	76	18.58%
	41 years old and above	56	13.69%
Occupation	Businessman	62	15.16%
	Student	175	42.79%
	Official staff	116	28.36%
	Others	56	13.69%
Income	Less than 5 million VND	131	32.03%
	From 5 to less than 10 million VND	113	27.63%
	From 10 to less than 20 million VND	91	22.25%
	20 million VND and avove	74	18.09%
Frequency of service usage	Once a month	214	52.32%
	2-4 times per month	151	36.92%
	More than 5 times per month	44	10.76%

4.2 Evaluating the measurement model

The primary objective of assessing the measurement model is to evaluate the suitability of the latent variables and their indicators. Specifically, this stage involves testing various aspects such as indicator reliability, internal consistency, convergent validity, and discriminant validity. The corresponding data are presented in Table 3. This study assessed construct reliability using Cronbach's alpha and Composite Reliability coefficients. Hair et al. [30] suggest that outer loading values exceeding 0.7 indicate good indicator reliability. In Table 3, both Cronbach's alpha and Composite Reliability coefficients surpassed the recommended threshold. However, while the overall measurement model demonstrated good construct reliability, eight items from various factors were excluded from further analysis. These items (EM1, FA1, FA5, RE4, RE5, CL4, and CL5) exhibited outer loading values below the recommended threshold of 0.7. This exclusion helps ensure the accuracy and robustness of the remaining measures.

Convergent validity, assessed by using Average Variance Extracted (AVE), was confirmed in this study. Hair et al. [30] suggest an AVE threshold of 0.50 for satisfactory convergent validity. The AVE values in this study ranged from 0.594 to 0.753, exceeding the recommended threshold and thus, confirming the convergent validity (as indicated in Table 3).

Discriminant validity examines the uniqueness of the measured construct, showing it is distinct from other constructs. The most common correlation technique used for this assessment is the Fornell-Larcker criterion. Discriminant validity is affirmed if the square root of each measured construct's Average Variance Extracted (AVE) exceeds its correlation with any other measured construct [30]. In this study, the Fornell and Larcker criterion was applied to assess discriminant validity, with the results presented in Table 4. The diagonal values in Table 4 represent the square root of the AVE, and they surpass the off-diagonal values, indicating no correlation between any two measured constructs. Therefore, this confirms the discriminant validity of the research model.
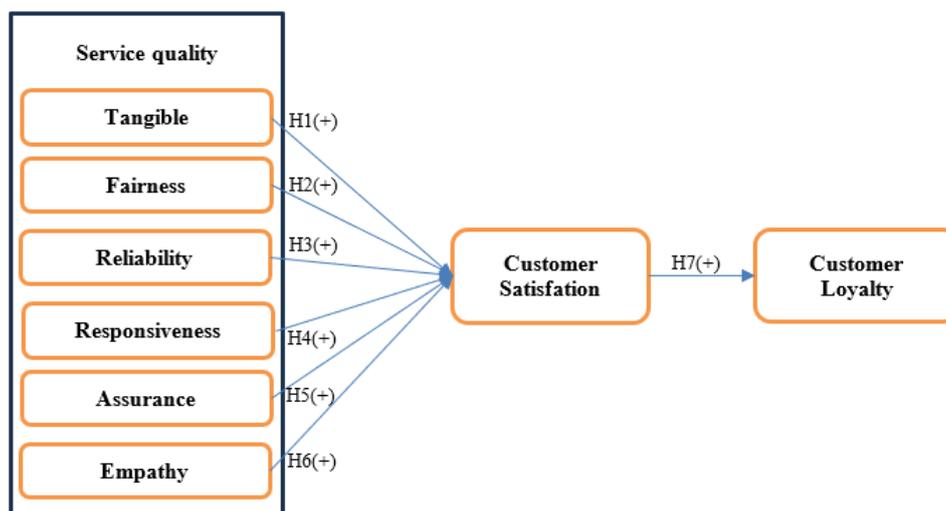
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Table 3 Reliability and AVE

Constructs	Measurement	Outer loadings	Cronbach's Alpha	CR	AVE
Tangibles (TA)	TA1	0.756	0.860	0.898	0.639
	TA2	0.821			
	TA3	0.840			
	TA4	0.803			
	TA5	0.774			
Fairness (FA)	FA2	0.807	0.836	0.902	0.753
	FA3	0.848			
	FA4	0.826			
Reliability (RE)	RE1	0.764	0.825	0.894	0.737
	RE2	0.803			
	RE3	0.811			
Responsiveness (RES)	RES1	0.763	0.829	0.880	0.594
	RES2	0.813			
	RES3	0.792			
	RES4	0.770			
	RES5	0.712			
Assurance (AS)	AS1	0.732	0.846	0.897	0.686
	AS2	0.852			
	AS3	0.844			
	AS4	0.812			
Empathy (EM)	EM2	0.749	0.784	0.856	0.599
	EM3	0.789			
	EM4	0.760			
	EM5	0.773			
Customer satisfaction (CS)	CS1	0.751	0.835	0.884	0.604
	CS2	0.802			
	CS3	0.816			
	CS4	0.795			
	CS5	0.716			
Customer Loyalty (CL)	CL1	0.825	0.830	0.898	0.746
	CL2	0.858			
	CL3	0.860			

Table 4 Fornell-Larcker criterion

	AS	CL	CS	EM	FA	RE	RES	TA
AS	**0.828**							
CL	0.345	**0.863**						
CS	0.440	0.644	**0.777**					
EM	0.288	0.408	0.626	**0.774**				
FA	0.108	0.336	0.495	0.284	**0.868**			
RE	0.201	0.037	0.225	0.189	0.113	**0.859**		
RES	0.380	0.425	0.624	0.454	0.311	0.262	**0.771**	
TA	0.167	0.190	0.338	0.271	0.191	0.132	0.254	**0.799**

4.3 Evaluating the structural model

The next analysis tests the hypotheses within the structural model (Figure 2). As detailed in Table 5, six out of seven proposed hypotheses were supported. Six dimensions of service quality demonstrated significant positive influences on customer satisfaction: Tangibility ($\beta = 0.089$, $p < 0.05$), Fairness ($\beta = 0.271$, $p < 0.05$), Responsiveness ($\beta = 0.291$, $p < 0.05$), Assurance ($\beta = 0.187$, $p < 0.05$) and Empathy ($\beta = 0.338$, $p < 0.05$). In other words, the hypotheses H1, H2, H4, H5, and H6 were supported. Furthermore, the findings revealed that Empathy possessed the strongest positive impact on customer satisfaction among the six constructs investigated. Similarly, customer satisfaction ($\beta = 0.644$, $p < 0.05$) also exerted a significant positive effect on customer loyalty, confirming the direct effect hypothesis (H7). Nevertheless, one

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dimension of logistics service quality did not impact customer satisfaction: Reliability ($\beta = 0.005$, $p > 0.05$). Thus, the hypothesis H3 was rejected ($\beta = 0.005$, $p = 0.887$).
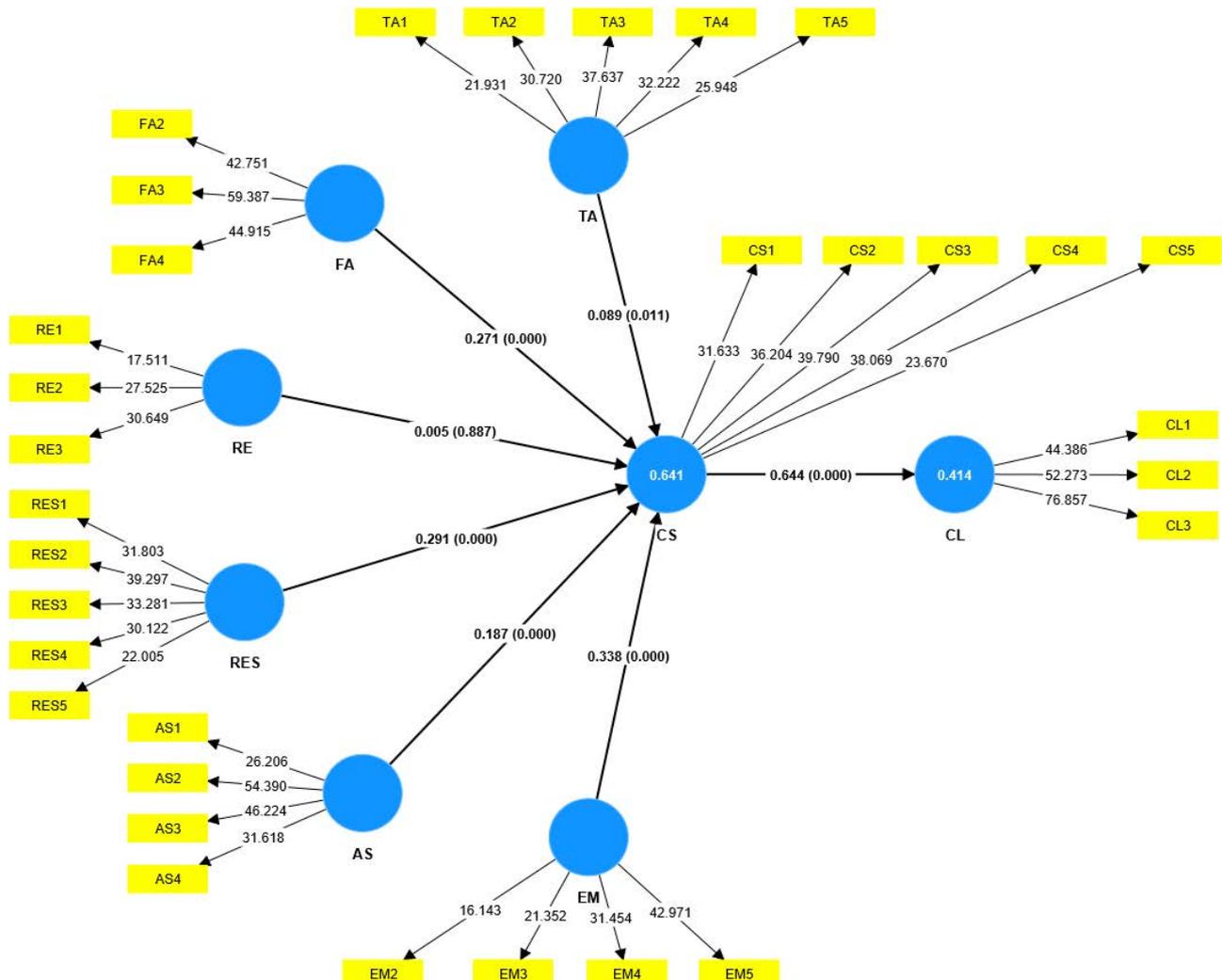
Figure 2 The results of the structural model analysis

This study also evaluated the effect sizes of the hypothesized relationships using the f^2 statistic. The f^2 indicates the proportion of variance in an endogenous variable that can be attributed to a specific exogenous variable. As detailed in Table 5, the calculated f^2 values were 0.02, 0.15, and 0.35, corresponding to weak, moderate, and strong effects, respectively. Empathy, fairness, and responsiveness exerted a medium effect on customer satisfaction, while assurance and tangibles exhibited a small effect. These findings provide valuable insights into the relative impact of each factor on customer satisfaction.

Table 5 Structural path analysis

Hypotheses	Coefficients	f^2	P values	Conclusion
H1: Tangibles → Customer satisfaction	0.089	0.020	0.011	Accepted
H2: Fairness → Customer satisfaction	0.271	0.177	0.000	Accepted
H3: Reliablity → Customer satisfaction	0.005	0.000	0.887	Rejected
H4: Responsiveness → Customer satisfaction	0.291	0.158	0.000	Accepted
H5: Assurance → Customer satisfaction	0.187	0.081	0.000	Accepted
H6: Empathy → Customer satisfaction	0.338	0.233	0.000	Accepted
H7: Customer satisfaction → Customer loyalty	0.644	0.707	0.000	Accepted

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4.4 Discussion

This study investigates the determinants of customer satisfaction and loyalty with logistics service companies in HCMC, Vietnam. Five dimensions - tangibles, reliability, responsiveness, assurance, empathy, and fairness - are positively related to customer satisfaction. As shown in Table 5, the path coefficient of empathy is the strongest predictor (0.338). This factor plays the most crucial role in customer satisfaction. The second strongest predictor for customer satisfaction is responsiveness, with a coefficient of 0.291, which is compatible with [31]. Assurance and tangibles also significantly affect customer satisfaction, supporting [32]. Besides that, the result reveals that service fairness also impacts customer satisfaction, which confirms the recent research by Kwortnik & Han [33] and Seider & Berry [12]. By incorporating fairness into their service strategies, logistics companies can go beyond simply meeting basic service needs to build stronger customer relationships, as mentioned in Seider & Berry [12]. It can be concluded that research across various areas has consistently highlighted the significant correlations and direct impacts of service quality on customer satisfaction [34].

There is no doubt that the service quality of logistics providers significantly enhances customer satisfaction, which in turn fosters customer loyalty. Our findings provide further evidence to support previous research, such as Slack et al. [35]. The authors identified a significant and positive relationship between service quality and both customer satisfaction and loyalty. They further revealed that service quality has a direct impact on loyalty, and also an indirect impact mediated by customer satisfaction.

Contrary to our expectations, the hypothesis H3 was rejected. This suggests that reliability did not exhibit a significant association with customer satisfaction in Ho Chi Minh City. The disconnection between reliability and customer satisfaction in Ho Chi Minh City likely stems from several reasons specific to the city's context. As a busy metropolis and a major economic hub in Vietnam, Ho Chi Minh City might have different customer preferences and expectations compared to other areas. This could lead to a different perception of reliability among Ho Chi Minh City customers. Additionally, the logistics landscape in Ho Chi Minh City may present unique challenges or features that diminish the importance of traditional reliability measures. For instance, logistical complexities in terms of traffic congestion, inefficient infrastructure, or complex supply chains might make strict adherence to timelines less significant for customers in urban areas like Ho Chi Minh City. Furthermore, cultural or industry-specific aspects within Ho Chi Minh City's logistics sector could influence how customers perceive reliability compared to other areas or industries. Recognizing these specific details is crucial for accurately determining the factors that truly drive customer satisfaction in Ho Chi Minh City's logistics scene.

5 Conclusion

Building upon the SERVQUAL framework, the study extends the model by incorporating fairness, which is shown to enhance its explanatory power. Furthermore, integrating fairness into the model provides a theoretical foundation for understanding how users engage with logistics services. The study operationalizes the SERVQUAL dimensions specifically within the context of services offered by logistics companies and examines their conceptual influence on customer satisfaction and customer loyalty. This study contributes to the existing body of research by replicating previous findings on the significant influences of service quality on customer satisfaction and loyalty. In other words, the results validate the positive and significant impacts of these factors on customer satisfaction and loyalty within the logistics industry.

Drawing from the research findings, the author suggests several managerial strategies for logistics companies in Ho Chi Minh City to elevate customer satisfaction. Firms are advised to focus on enhancing tangible aspects, such as upgrading facilities and standardizing employee uniforms, to foster a professional atmosphere. Additionally, to promote fairness, meticulous recruitment and comprehensive training are essential to equip staff with the skills necessary for exceptional customer care. The implementation of AI tools on company websites can enhance responsiveness, providing prompt information to clients when staff availability is limited. Assurance can be strengthened by transparent communication of procedures, thereby cultivating trust in the services offered. Empathy can be further developed by refining customer service skills. Furthermore, fostering customer loyalty involves regular engagement and the offering of promotional incentives that keep the brand at the forefront of customers' preferences.

This research, similar to many prior studies, has limitations that need further exploration. First, the sample size of 409 participants recruited solely from Ho Chi Minh City limits the generalizability of the findings. Future research should consider expanding the sample size and diversifying the study scope to obtain a more representative overview. Second, while the study focuses on service quality factors, brand reputation and pricing also contribute to customer satisfaction. Future research should consider incorporating these elements for a more comprehensive understanding. Finally, the construct of reliability did not significantly impact customer satisfaction in this study. This discrepancy might be attributed to a mismatch between the survey instrument and the specific context of Ho Chi Minh City logistics services. Therefore, future studies should refine, validate, and potentially enhance the questionnaire to better reflect the local environment. By addressing these limitations, future studies can build upon this research to provide a more robust and generalizable understanding of customer satisfaction in the Ho Chi Minh City logistics landscape.

Unlocking the potential of logistics service quality: insights into customer satisfaction and loyalty via an extended SERVQUAL approach
Anh Tho To, Nguyen Thu Huynh, Thi Minh Thanh Dang, Thi Hong Minh Trinh, Thi Xuan Thao Pham

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Application of machine learning to storage allocation decision making system within air cargo terminals

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Abstract: The rapid growth of global air cargo demand has intensified the need for more efficient and intelligent storage allocation within airport cargo terminals. Traditional static allocation and rule-based systems struggle to adapt to dynamic cargo flows, leading to operational inefficiencies. This study aims to develop a hybrid decision support system that optimizes storage allocation by integrating machine learning and multicriteria decision-making techniques. A Random Forest Classifier was trained using historical cargo data, including weight, quantity, size, priority, and cargo type, to predict optimal storage zones. To enhance interpretability and expert control, the Analytic Hierarchy Process AHP was used to derive feature weights, while the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was employed to rank the best storage alternatives. The model was tested on real-world data from Almaty International Airport involving 1,500 cargo orders. Results show that the system reduced average storage time by 14%, minimized cargo redistributions by 22%, increased storage density by 9%, and improved on-time delivery for priority cargo by 17% compared to traditional FIFO-based methods. The integration of data-driven learning with expert judgment offers a robust and transparent decision-making framework. These improvements confirm the value of combining machine learning with AHP–TOPSIS methods in logistics operations. This system presents significant implications for airport terminal managers seeking to enhance operational throughput, academic researchers exploring hybrid intelligent systems, and policymakers promoting digital logistics infrastructure. Future studies may include adaptive learning, seasonal cargo flow modelling, and digital twin-based scenario testing to further generalize the solution.

1   Introduction

The worldwide increase in e-commerce and the continually rising need for quicker freight transportation have created significant pressure on air cargo terminals to enhance operational effectiveness, accuracy, and flexibility. Given that air transport is crucial for just-in-time delivery systems, effectively and precisely managing cargo storage has emerged as an essential element for maintaining performance and competitiveness. However, managing the increasing complexity of cargo—where each unit varies in size, importance, weight, and destination—poses a daily logistical difficulty. Terminals must manage a great amount of goods, often with rigid time and space parameters. The inadequacy of conventional rule-based systems in high-speed environments, which rely on fixed zoning, basic heuristics, or manual decisions, is becoming apparent. First-in, first-out (FIFO) and fixed spatial assignment techniques, which once served the needs of the less complex tasks, can no longer keep up with the pace and randomness of modern air logistics. The worldwide development of e-commerce and the increasing demand for faster freight turnaround have strongly encouraged air freight terminals to enhance the effectiveness, accuracy, and adaptive characteristics of operations. Air transportation is an essential part of a just-in-time delivery network, so it is significant to ensure the accurate and efficient management of cargo storage to preserve performance and competitiveness [1]. The rising complexity of the cargo, with each unit being of a different size, urgency, weight, and destination, represents a continuing logistical problem. Terminals handle large numbers of

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cargo, often within strict time constraints and limited space. The traditional rule-based systems, which operate on predetermined zoning, single heuristic, or even human choices, are not adequate in these dynamic environments.

These ancient methods reveal a lot of inefficiencies as operations become more complex. Maladjusted storage space, unnecessary cargo manipulations, and unused warehouse areas hinder order picking and promote risks of damages, labour costs, and human mistakes. Furthermore, the extended application of online tracking services and automation systems highlights the possibility of improvement. Despite increasing transparency, a lot of warehouses still do not fully utilize the capabilities of these technologies. Traditional warehouse systems cannot handle the dynamic cargo traffic in the modern world, and these disadvantages are increasingly becoming intolerable in an industry where time and correctness play a crucial role in reputation and profits [2].

To address this the logistics sector has begun to implement more smart logistics that use data, algorithms, and automation to enhance decision-making. One of them, machine learning (ML), deserves mentioning because of its ability to uncover complex structures in operational data, which are too elusive to be detected by a classic rule-based reasoning approach. ML enables the predictive real-time allocation of storage locations to continuously learn based on historical data and adapt to the present circumstances [3]. It considers several interacting parameters such as cargo weight, dimensions, urgency of delivery, and available space now. Despite its usefulness in the wider logistics setting, e.g., route optimization, demand prediction, and inventory management, the application of machine learning to warehouse operation remains limited, especially in air cargo terminals where fast and accurate micro-decisions are crucial [4].

This research is intended to fill that gap by proposing a new hybrid decision-support system dedicated to the air cargo terminal environment. The resulting system is an explainable and adaptable expert machine learning system designed for predictive cargo storage allocation. The developed system uses a Random Forest classifier to predict storage areas for incoming shipments based on key characteristics of the cargo. Rather than depending on predictions from a black-box process, it integrates two known multicriteria decision-making (MCDM) methods, the AHP and the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS). They integrate knowledge of the field into the methods, discerning priorities such as urgency, space, and accessibility to be logical upon [5].

To validate the model, a real-life dataset of 1,500 cargo entries was taken at the Almaty International Airport. All the records include such parameters as cargo volume, weight, type, and the urgency of delivery. Its practical benefits are proved by the comparison with the traditional methods used in the warehouse and other machine learning models: Support Vector Machines (SVM), Decision Trees, and Logistic Regression. The results are remarkable: an average storage time decreased by 14%, cargo repositioning decreased by 22%, space usage increased by 9%, and the timely handling of priority cargoes rose by 17%. Moreover, the Random Forest model with a classification accuracy of 61% outperformed the SVM (41.5%), Decision Trees (39%), and Logistic Regression (37%) [6]. These findings highlight the technical soundness of the system in addition to its practical effectiveness in intensifying the throughput and response of the warehouse. Regarding academic contribution, this study helps in several areas. Firstly, it formalizes a systematic approach to storage allocation as it identifies and encodes operation variables that are crucial and influence cargo handling. Second, it signifies the effectiveness of ensemble-based classifiers on handling complex and multiclass classification problems in warehouse logistics. Third, it presents a new approach, which incorporates explain ability in algorithmic decision-making, which is becoming a more important factor in the practical acceptability of AI-based systems. The latter enables warehouse managers to understand and have confidence in the logic of automated decisions, which is essential to accept them [7]. Nevertheless, the research also acknowledges the limitations. The model has been only trained on the data of a single terminal at Almaty International Airport and might require modifications when applied to other places that have different layouts, cargo compositions, or regulatory environments [8]. Besides, although the model is effective when applied in a batch-processing setting, it is yet to include real-time sensor data and consider dynamic variables like varying demand, labour adjustments, or weather effects. The future work needs to focus on making the system more adaptive, i.e., live sensor feeds, seasonal forecasting modules, and adaptive learning (e.g., reinforcement learning). The digital twin of the warehouse would also allow testing allocation strategies virtually, improving the model in various operation conditions [9].

This research addresses a clear and timely need within the air cargo industry for a smarter, faster, and more interpretable storage assignment system. By combining predictive machine learning with expert-informed decision frameworks, it introduces a powerful tool for transforming air cargo logistics at the warehouse level. The findings confirm that intelligent, hybrid systems can dramatically improve both operational metrics and decision confidence—paving the way for broader implementation across high-volume cargo hubs and setting a new standard for smart logistics innovation [10].

2 Methodology
2.1 Description of the case study

Modern airport cargo terminals are key elements in the global supply chain because of their speed of operation and accurate handling of large volumes of cargo. The main factor affecting the efficient operation of cargo terminals is the productivity of warehouse facilities. The method proposed in this paper represents a typical warehouse structure with

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multiple storage sectors and unique designations for easy navigation. Each storage area is intended for different cargo categories, taking priority into account.

The dataset for training the model contained 1,500 orders with various parametric characteristics, such as weight and volume, product type, and delivery priority. One feature of this dataset is the presence of a variety of goods. Some of the goods presented in the dataset are high priority, requiring minimal storage time and quick availability. Such diversity allows modelling decision making under conditions of multicriteria uncertainty.

2.2 Data collection and pre-processing

The data for the model were obtained from a dataset that contained 1,500 records, each representing a specific order. An order includes the following attributes: order and product identifier, unit quantity, priority, cargo type, weight, and size. The key variable that must be determined is the storage zone, which represents the class of cargo belonging to one of the available sectors in the warehouse. The first stage involved preparing features to ensure the correct operation of the model. The check for outliers and anomalies in the weight and quantity features was performed using an interquartile range. For better operation of the model, the categorical feature priority, size, and product type were converted to a numeric format. The priority feature is encoded in the binary number system and is presented in Equation (1):

$$Priority = \begin{cases} 1, if\ Priority = "High" \\ 0, if\ Priority = "Low" \end{cases} \tag{1}$$

The remaining categorical features were recoded using one-hot encoding to unify the binary variables. For each categorical feature of the set of categories (X), a vector is created in which only one variable is equal to one, and all the others are zero, which avoids false ordering of categories. The numerical features of the weight and quantity of units of goods are reduced to a single scale min - max normalization according to Equation (2):

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{2}$$

where x is the original value of the feature, x_{min} and x_{max} are the minimum and maximum values of the sample.

The normalization given in Equation (2) is critical for optimizing the correctness of the algorithms that are sensitive to feature scaling. After the decoding and normalization processes, the dataset was divided into two sets: training and testing (80:20). A class balance check for the target location value was also performed using the frequency distribution estimation method to ensure a fair prediction across all possible storage locations.

2.3 Machine Learning Model Design

At this stage, a predictive model is being built that will allow automatic recommendations of the optimal zone for storing cargo based on its input characteristics. The task of this model lies in multiclass classification, in which each class corresponds to one of the available warehouse zones. A random forest classifier (RFC) model was used to solve this problem. This model is characterized by parameters such as resistance to overfitting and the ability to process mixed types of data, and has convenient means for assessing the importance of a particular feature. RFC is a sequence of n decision trees trained on various subsamples with bootstrapping, and the presentation is carried out by the \"majority vote\" method, which is presented in Equation (3):

$$\hat{y} = mode\{T_1(x), T_2(x), \dots, T_n(x)\} \tag{3}$$

where $T_n(x)$ is the prediction of the n tree.

The input features for the RFC model are the number of units in order, weight, dimensions, and product type. The results were validated using stratified partitioning, which preserves the distribution of classes in the samples. The accuracy (4), precision (5), recall (6), F1 - score (7), F1 for macro averaging (8), and error matrix are used to evaluate the model's performance.

$$Accuracy = \frac{1}{N}\sum_{i=1}^{N} I(y_i = \hat{y}_i) \tag{4}$$

where N is the number of objects, y_i is the true class label, $\hat{y}_i$ is the predicted class label, I is the function identifier.

$$Precision_k = \frac{TP_k}{TP_k + FP_k} \tag{5}$$

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$$Recall_k = \frac{TP_k}{TP_k + FN_k} \tag{6}$$

$$F1_k = \frac{2 \cdot Precision_k \cdot Recall_k}{Precision_k + Recall_k} = \frac{2 \cdot TP_k}{2 \cdot TP_k + FP_k + FN_k} \tag{7}$$

$$F1_{macro} = \frac{1}{k}\sum_{k=1}^{k} F1_k \tag{8}$$

Confusion was introduced into the model to visualize the classification errors. The matrix represents the frequency indices of correct and erroneous predictions for each class.

2.4 Integration with decision support system

To increase the interpretability and flexibility of the decisions made by the system, a hybrid decision support system is integrated into the machine learning model, which includes the Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Integration of these methods allows for the consideration of, in addition to empirical patterns, expert preferences and the weights and priorities of each parameter. In the first stage, the system used the AHP method to calculate the weights of the criteria required to select a storage area. In this system, to obtain the weights of each criterion, a matrix of pairwise comparisons is formed based on an expert assessment conducted with the participation of representatives of the Almaty International Airport JSC. The consistency indicator (CI) is determined by Equation (9) and is used to assess the consistency of judgments in the matrix of pairwise comparisons. Next, the consistency coefficient (CR) was calculated using Equation (10) for normalization and consistency testing.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{9}$$

where λ_{max} is the largest eigenvalue of the matrix, n is the number of criteria.

$$CR = \frac{CI}{RI} \tag{10}$$

where RI is the random agreement index.

After determining the weights of the parameters, it is necessary to rank the storage zones using the TOPSIS method. This method was chosen because of the search for alternatives that are closest to the ideal solution and most distant from the anti-ideal solution. To apply the TOPSIS method in this study, the following action algorithm was developed:

Step 1. Construction of a normalized decision matrix.

Step 2. Weighing the matrix parameters considering the weights obtained from the AHP method based on Equation (11):

$$v_{ij} = w_j \cdot r_{ij} \tag{11}$$

where w_j is the weight of the criterion, r_{ij} is the normalized value of criterion j for alternative i.

Step 3. The definition of positive and negative ideal values is given in Equations (12) and (13).

$$A^+ = \{\max(v_{ij})\} \tag{12}$$

$$A^- = [\min(v_{ij})\} \tag{13}$$

Step 4. Distances to the maximum and minimum values are calculated using Equations (14) and (15).

$$D_i^+ = \sqrt{\sum_j (v_{ij} - A_j^+)^2} \tag{14}$$

$$D_i^- = \sqrt{\sum_j (v_{ij} - A_j^-)^2} \tag{15}$$

Step 5. At the last step, the proximity coefficient is calculated in accordance with Equation (16):

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$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \qquad (16)$$

In this scenario, the alternative with the highest value is the most preferred C_i.

The integration of the proposed architecture into the machine-learning model involves the use of a filter in the first stage, which narrows the set of possible storage locations to a subset of the most probable ones. Subsequently, a hybrid decision support model is applied to this subset to rank the results by considering expert assessments and system constraints. When integrating these methods and machine learning methods, a two-stage hybrid approach is implemented, which contains the following features: learning ability and generalization of machine learning, transparency and control of expert weights using the AHP method, and ranking accuracy in multicriteria selection using the TOPSIS method. The proposed approach is especially effective under conditions of uncertainty, system adaptability, and peculiarity of the logistics decisions made.

2.5 Experimental procedure

This research was carried out through a structured, multi-phase process involving data acquisition, pre-processing, machine learning model development, integration of expert judgment using AHP-TOPSIS, and validation using operational KPIs. Initially, a dataset of 1,500 historical cargo orders was collected from the WMS of Almaty International Airport JSC. Each order included relevant parameters such as weight, quantity, dimensions, cargo type, priority level, and the corresponding storage zone. The dataset captured six months of real operational activity and contained a mix of high-priority and standard cargo items.

Data pre-processing was conducted to prepare the raw dataset for analysis. Outliers in numerical features such as weight and quantity were identified and removed using the interquartile range (IQR) method. Categorical variables such as cargo type and size were encoded using one-hot encoding to prevent false ordering, while the binary priority feature was encoded using a 0–1 scheme. Numerical features were normalized using min-max scaling to ensure uniform feature influence during model training. The final dataset was split into training (80%) and testing (20%) sets using stratified sampling to preserve class distribution across storage zones.

FFC was employed due to its robustness, resistance to overfitting, and capability to handle mixed data types to classify. The RFC was trained using 100 decision trees, and predictions were aggregated via majority voting. The model's performance was assessed using standard classification metrics, including accuracy, precision, recall, F1-score, and confusion matrix analysis. For benchmarking, alternative models—Support Vector Machine (SVM), Decision Tree, and Logistic Regression—were also tested using the same dataset.

To enhance the interpretability and transparency of the decision-making process, a hybrid decision support system incorporating the AHP and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was integrated with the machine learning model. AHP was used to derive the relative importance of decision-making criteria through pairwise comparisons provided by six logistics experts from the airport. The consistency of these judgments was confirmed by calculating the consistency ratio (CR), and only matrices with CR < 0.1 were accepted. The resulting criterion weights were then used in the TOPSIS procedure to rank potential storage zones for each cargo order. The TOPSIS method involved building a normalized decision matrix, applying the AHP weights, identifying ideal and anti-ideal solutions, computing Euclidean distances to these solutions, and finally calculating a closeness coefficient to determine the most suitable storage zone.

The integrated hybrid system operated in two stages: initially, the RFC model narrowed down probable storage zones; subsequently, the AHP–TOPSIS method ranked these zones by incorporating expert preferences. This two-tiered architecture ensured both predictive efficiency and decision-making transparency. To evaluate the effectiveness of the proposed system, a pilot implementation was carried out in a real warehouse environment. Key performance indicators (KPIs), including average storage time, number of cargo redistributions, storage density, and on-time delivery of priority shipments, were measured before and after system deployment. The new system demonstrated significant improvements across all KPIs when compared to traditional FIFO and static zoning strategies.

3 Results and discussion

3.1 Formalization of factors for choosing a storage area

The main factor in building a digital model to support decision making in an air cargo terminal is the formalization of factors that influence the procedure for selecting a storage area. For the logical distribution of objects within the warehouse, the selection and structuring of a set of features necessary to account for the high dynamics of cargo flow at the Almaty International Airport JSC were used. In the initial stage of the study, an analysis of the technological cycle of cargo logistics processing was conducted. Consequently, the main metrics that directly affect the process of selecting a cargo storage location were selected. These metrics were classified according to data type and source of origin, as shown in Table 1. The model includes quantitative indicators (weight, quantity, and frequency of access to cargo) and categorical features (cargo type and size).

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Table 1 Formalized factors and their classification

	Factor	Data type	Coding method	Data source
1	Weight of cargo	Numerical	Min-max normalization	Application/invoice
2	Cargo size	Categorical	One-hot encoding	Application/WMS system
3	Type of cargo	Categorical	One-hot encoding	Product Catalogue
4	Priority delivery	Binary	Binary encoding	Priority Management System
5	Number of units	Numerical	Min-max normalization	Bid
6	Distance to the loading area	Numerical	Min-max normalization	Warehouse plan/route
7	Frequency of access to cargo	Numerical	Min-max normalization	Access log/ WMS
8	Current storage area occupancy	Numerical	Min-max normalization	Warehouse monitoring system

Categorical variables, such as product type and size, are pre-processed with one-hot method encoding to eliminate false hierarchical information when working with machine learning models. The binary variable priority is encoded using the 1/0 scheme. Quantitative variables were normalized using min - max scaling to ensure a single scale of the feature vector, which ensured the stability of the algorithms during training. To identify the important patterns, a histogram of the distribution of laws by product was constructed, including type and size (Figure 1) [11].
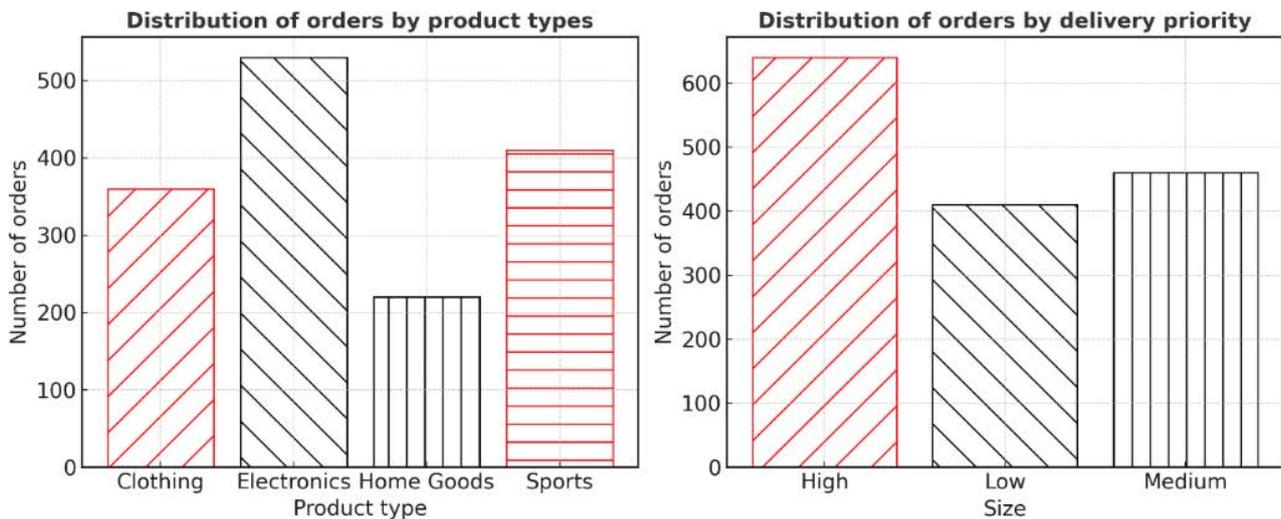
Figure 1 Histogram of order distribution by Product characteristics type and size

Figure 1 shows the histogram of order distribution categorized by product type (left) and delivery priority (right), offering insights into the diversity and urgency of cargo handled within the air cargo terminal. On the left side of the figure, product types are grouped into Clothing, Electronics, Home Goods, and Sports. Among these, Electronics represent the highest volume, accounting for approximately 530 orders, which is about 45% more than Clothing (around 365 orders) and 140% higher than Home Goods (around 220 orders). This substantial dominance of electronic goods could be attributed to their high demand in air transport due to value density and time sensitivity. Clothing and sports items also show a significant share of the volume, with sports-related shipments slightly exceeding clothing by approximately 12% [12]. The lowest category, Home Goods, may reflect the bulkier nature or lower frequency of air shipping for household items, which are often shipped via slower, ground-based logistics. The right side of the figure shows the distribution by delivery priority. High-priority orders lead with over 630 entries, significantly ahead of medium (approximately 460) and low-priority orders (around 410). This reflects a roughly 37% higher volume of high-priority orders compared to medium-priority, and about 54% more than low-priority. The prominence of high-priority shipments emphasizes the operational necessity for swift sorting, optimized storage, and timely dispatch systems. E-commerce express services, just-in-time manufacturing components, or medical and time-critical deliveries could drive this. The figure highlights the dominance of electronic and high-priority goods, underscoring the importance of responsive, data-driven storage strategies that accommodate both product type variability and urgency, directly supporting the objectives of the hybrid classification model implemented in this study [13]. The most delivered types of goods to the warehouse are electronics, sports equipment, clothing, and household goods, which should be considered when selecting storage areas. It is also worth noting that many high-priority goods require this logistic criterion to place goods in a quick-access area. When pre-

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processing the machine learning model, special attention was paid to the relationships between features. For this purpose, a correlation heat map was constructed between the features (Figure 2) [14].
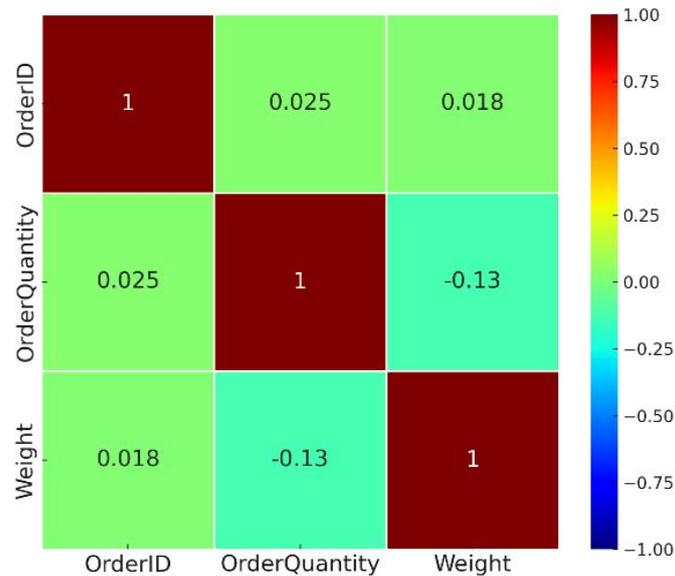
Figure 2 Correlation heat map between features

Figure 2 shows the correlation heat map between key numerical features—Order ID, Order Quantity, and Weight—used in the machine learning model to classify cargo into appropriate storage zones. The matrix values reflect the Pearson correlation coefficients, which quantify the linear relationship between pairs of variables on a scale from -1 to +1. As expected, the diagonal values are 1.00, indicating a perfect correlation of each variable with itself. Looking at the off-diagonal values, the correlation between Order ID and Order Quantity is 0.025, while the correlation between Order ID and Weight is 0.018, both of which are extremely weak and close to zero [15]. These low correlations (approximately 2.5% and 1.8%, respectively) suggest that Order ID is essentially a unique identifier and does not carry predictive relevance for quantity or weight. This aligns with expectations, as Order ID is typically a randomly or sequentially assigned number with no intrinsic operational meaning. The only moderately meaningful relationship is the correlation between Order Quantity and Weight, which is -0.13. This negative correlation implies that as the quantity of items in an order increase, the average individual weight of those items tends to decrease, and vice versa. Though weak (representing only a 13% inverse relationship), this trend can be logically explained: high-quantity shipments are often composed of lightweight or small items (e.g., clothing or electronics), whereas low-quantity orders may involve heavier goods like machinery or dense household products. This relationship supports the importance of both weight and quantity as distinct, influential parameters in the machine learning model's decision-making process for storage allocation. The figure confirms that Order Quantity and Weight hold valuable, independent information, while Order ID is non-contributory from a modelling perspective, justifying its exclusion from feature importance considerations. Analysis of the proposed heat map showed a positive interaction between the Order parameters Quantity and Weight. However, there is no correlation between the priority parameters and others, which indicates the independence of this feature. The obtained formalized features are theoretically substantiated and empirically verified when applied to a machine learning model [16]. Linking these features to operational KPIs will allow moving from static placement to the dynamically controlled and reproducible logic used in decision support systems.

3.2 Building a machine learning model

To solve the problem of automating the process of selecting the optimal cargo storage area inside the airport warehouse terminal, within the framework of this study, a machine learning model was developed and trained based on the classical Random Forest Classifier method. The model was trained based on Data Seta, which contained the quantitative and qualitative characteristics of the loads. This model was chosen because of a comparative analysis with other classical methods, SVM, decision tree, and logistic regression, based on the test sample. The results of the comparison of these methods are presented in Table 2.

The Random Forest model demonstrated superior classification performance compared to the other evaluated algorithms. As shown in Table 2, it effectively classified orders into the correct storage zones, underscoring its robustness and reliability. The error distribution across different algorithms is illustrated in Figure 3, providing further insight into model behaviour. In the case of Random Forest, the confusion matrix reveals a strong alignment of values along the

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diagonal, indicating a high rate of correct predictions. Conversely, the alternative models exhibit more prominent off-diagonal values, signifying a greater frequency of misclassifications. This dispersion of errors in other algorithms contributes to a noticeable decline in overall prediction quality [17].

Table 2 Comparison table of machine learning models

	Model	Accuracy	Precision	Recall	F1 Score
1	Random Forest	0.610	0.610	0.630	0.603
2	SVM (Linear)	0.415	0.423	0.432	0.403
3	Decision Tree	0.390	0.405	0.403	0.393
4	Logistic Regression	0.370	0.353	0.385	0.353
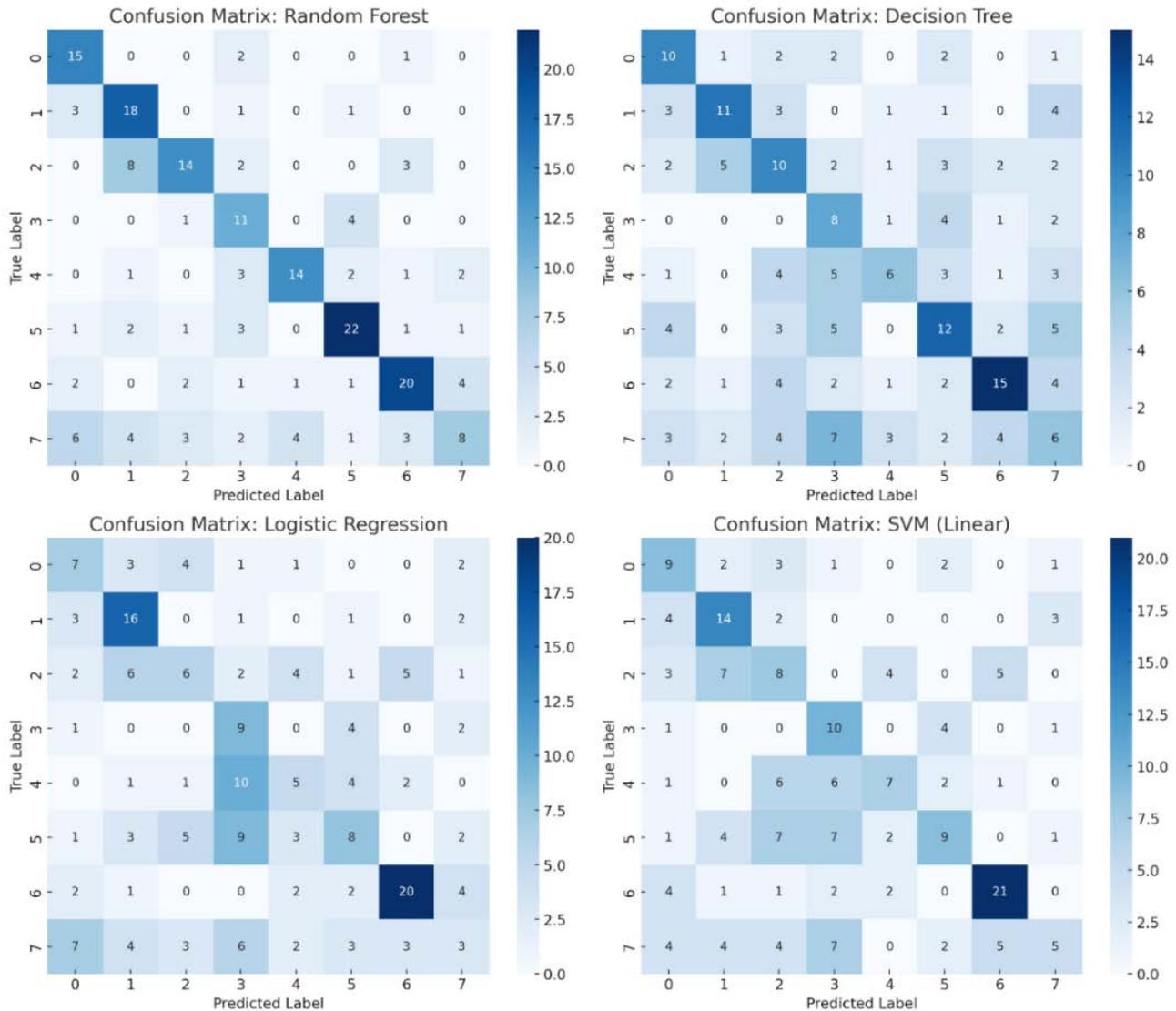
Figure 3 Confusion matrix

Figure 4 shows the feature importance diagram generated from the Random Forest model, which identifies the relative contribution of each input parameter to the accuracy of cargo storage zone classification. Among the eight evaluated features, Weight and Order Quantity emerge as the most influential, contributing approximately 42% and 36%, respectively. These two features alone account for nearly 78% of the model's predictive capability, highlighting their dominant role in distinguishing cargo handling and placement decisions. The high impact of weight is expected, as it directly influences storage logistics, safety considerations, and spatial constraints. Similarly, order quantity informs the volume requirements and potential for batch storage, explaining its strong influence. In contrast, categorical features such as Product Electronics (~5%), Product Clothing (~8%), and Product Household (almost negligible) show relatively low

importance. This suggests that product type has limited influence on the storage classification process, possibly due to the overlapping storage requirements among different categories of goods. Priority (High) holds moderate importance at around 9%, reinforcing the idea that the system accounts for delivery urgency, but not as significantly as physical attributes like weight or quantity. Interestingly, Size-related features (Small, Medium, Large) contribute less than 1% each, suggesting either a lack of sufficient variation in size data or that size information was embedded indirectly through correlated features like weight or volume [18]. This validates the system's reliance on measurable, operationally critical data for decision-making. It also justifies the AHP weighting method used in the study, ensuring that the model prioritizes features that genuinely impact performance, rather than those that are intuitively important but statistically weak.
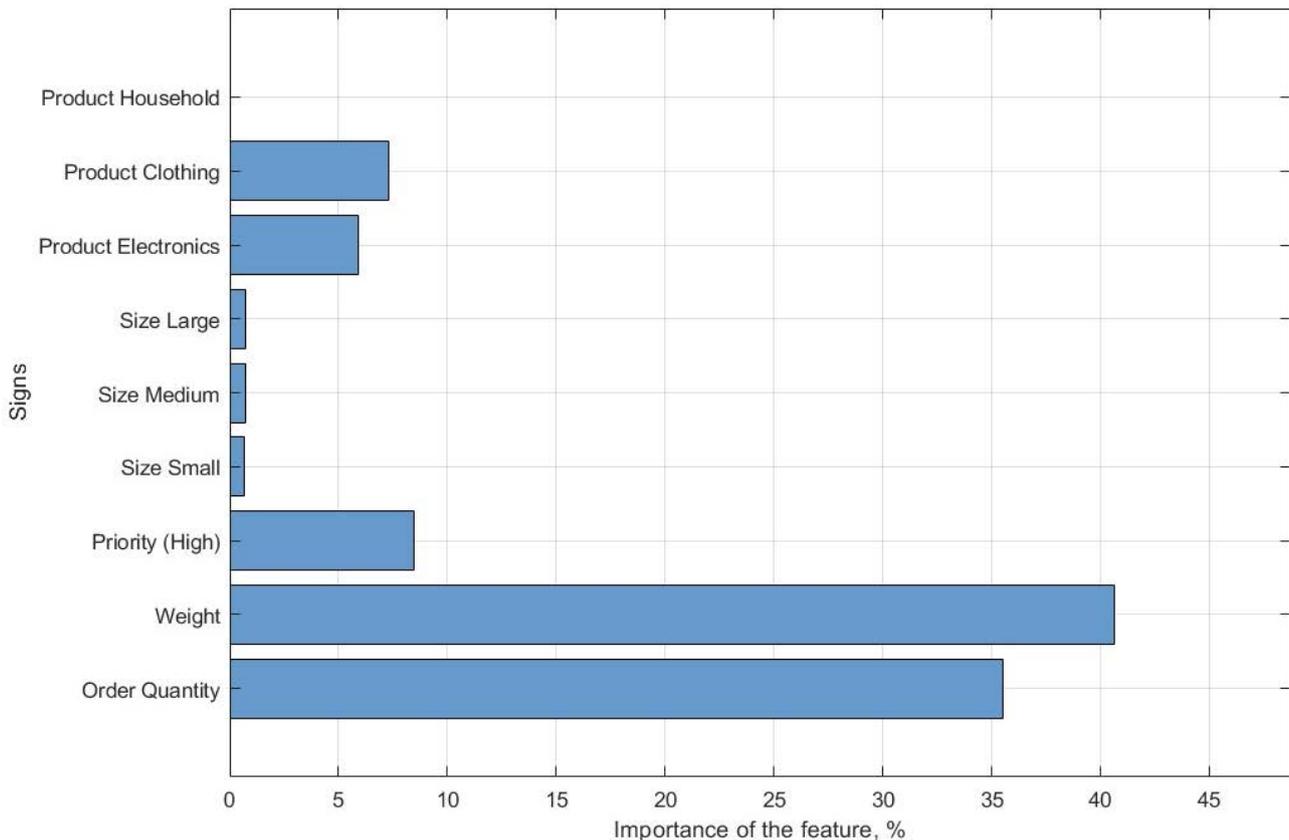
Figure 4 Feature importance diagram

The machine learning model based on the Random Forest algorithm demonstrated high suitability for practical applications in the initial stages of implementation. Based on the data obtained in this subsection, it can be concluded that the model has a stable and multiclass data-capable nature, which is applicable to a multicriteria structure of input data. The results obtained provide a solid basis for integrating the model into complex hybrid decision support systems and can also become a basic predictive block for the architecture of intelligent optimization in warehouse management processes [19].

3.3 Integration of AHP and TOPSIS into the system

To improve the interpretability and controllability of the processes for selecting the optimal storage zone in aviation warehouses, a decision support module based on the AHP and TOPSIS methods was added to the developed machine learning model. Thus, the approach will provide not only empirical patterns, but also expert assessments of the importance of each storage zone. In the first stage of the module implementation, the weights of the main criteria were introduced using the AHP method. Subsequently, a pairwise comparison of the features was performed. The results of the weight calculations are shown in Figure 5.

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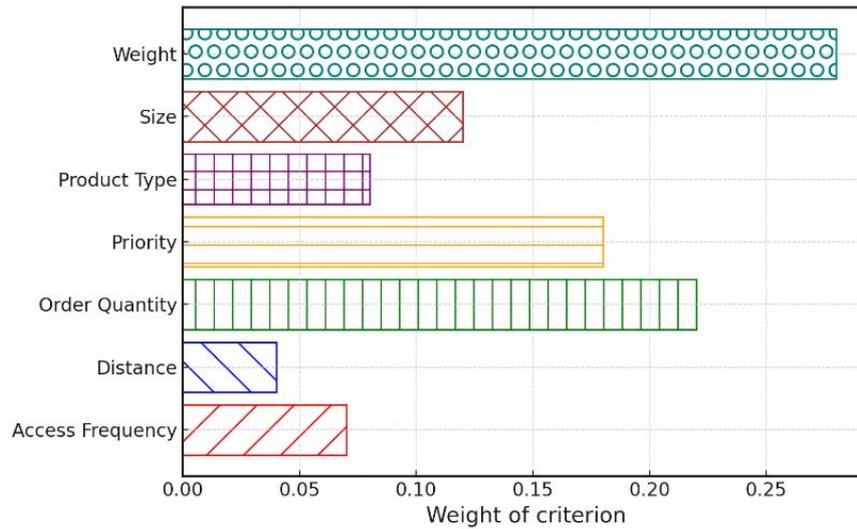
Figure 5 Criteria weight diagram

Figure shows the weight distribution of decision-making criteria used for evaluating cargo storage zone alternatives, as determined through the AHP. These weights represent the relative importance of each criterion—such as weight, size, product type, priority, and others—based on expert assessments that reflect real-world warehouse logistics priorities. Among the evaluated criteria, Weight holds the highest influence, with a normalized weight close to 0.27, indicating that nearly 27% of the total decision-making importance is attributed to this parameter. This strong emphasis can be explained by the physical and operational challenges associated with handling heavier cargo, such as load-bearing constraints, safety regulations, and handling equipment requirements [20]. Compared to Access Frequency, which holds the lowest weight at roughly 0.06, Weight is considered 350% more critical in determining optimal storage placement.
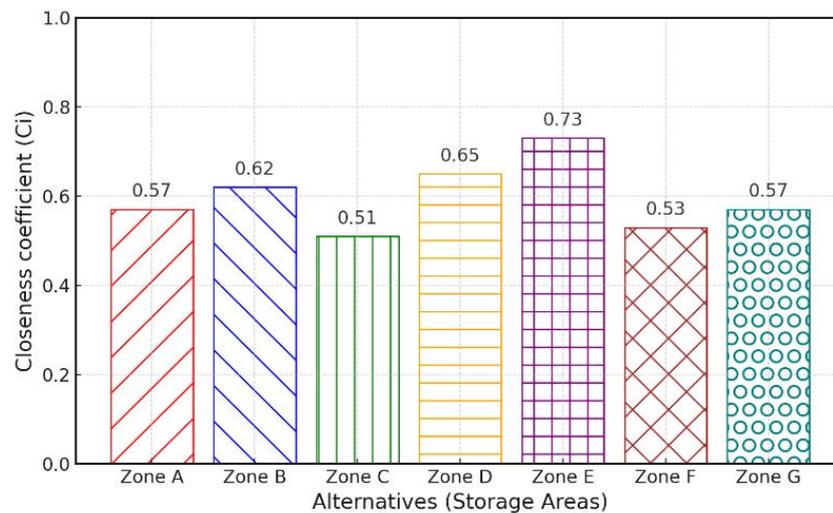
Figure 6 Graph of distances to the ideal solution

Order Quantity also plays a significant role, with a weight of approximately 0.21, showing that the volume of items in a shipment is a crucial factor—likely due to its impact on space utilization and grouping logistics. Priority ranks closely behind at around 0.18, reflecting the need to ensure fast access and timely handling for high-priority shipments. Size, while still relevant, holds a lower weight of about 0.12, suggesting that although dimensions affect storage fit, they may be somewhat correlated with weight or already embedded in handling strategy. Product Type contributes approximately 0.09, indicating that variations in item category (e.g., electronics, clothing) are moderately important but not as dominant. Distance, at 0.05, ranks second lowest, possibly due to the compact nature of warehouse layouts where inter-zone distances are relatively small [21].

In the next step, the weights of the criteria of the calculated AHP methods rank the storage area alternatives using the TOPSIS method. The distances to ideal and anti-ideal solutions were calculated to determine the degree of preference for each alternative. Figure 6 shows the closeness coefficient (Ci) values for each storage area alternative (Zones A to G),

derived using the TOPSIS method, which ranks the zones based on their proximity to an ideal solution. These coefficients reflect how well each zone meets the predefined criteria determined by expert judgments through AHP, such as accessibility, proximity, handling efficiency, and priority fulfilment. Among all the evaluated options, Zone E emerges as the most favourable, with a closeness coefficient of 0.73, indicating its strong alignment with operational and logistical priorities. When compared to Zone C, which has the lowest C_i value of 0.51, Zone E performs approximately 43.1% better in terms of closeness to the ideal. This significant difference suggests that Zone E likely offers superior access, optimized layout, and better readiness for handling priority cargo or high turnover loads. Zone D follows Zone E, with a C_i of 0.65, marking a 27.5% improvement over Zone C, and Zone B is next with 0.62, also outperforming Zone C by 21.6%. Zones A and G both have a coefficient of 0.57, slightly above the midpoint and 11.8% higher than Zone C, implying average alignment with the ideal criteria. Zone F, at 0.53, stands just slightly above Zone C, showing a 3.9% increase, but still underperforming relative to other zones. The ranking indicates that Zones E, D, and B are most suitable for immediate or frequent cargo placement, likely due to better spatial positioning, ease of access, or shorter loading times. On the other hand, Zones C and F may have constraints such as location at terminal extremes, narrow access lanes, or limited handling infrastructure. These insights support logistics managers in prioritizing high-demand or time-sensitive cargo for top-ranked zones while considering reallocation or layout enhancements for lower-ranked ones [22].

Building such a graph for each load demonstrates which storage zone is the most preferable. The approach of integrating machine learning methods, AHP and TOPSIS, allows the creation of a hybrid decision support system that considers not only the machine solution but also ensures transparency of the choice logic. The results obtained from the study confirm that the hybrid system not only allows for the automation of the process of placing loads, but also ensures validity, controllability, and adaptability to external conditions.

3.4   Assessing the effectiveness of a system using KPIs

To evaluate the efficiency of the proposed hybrid decision support system, tests were conducted in a real warehouse with the allocation of operational indicators (KPI). A comparison was carried out with the results of the traditional scheme of distribution of storage places based on the principles of FIFO and static zone assignments. Together with warehouse managers, the following key parameters for evaluation were defined: average storage time of cargo, number of cargo redistributions, coefficient of density of use of storage zones, and timeliness of priority shipments. The results of the comparison between the traditional and developed systems are shown in Figure 7.

The number of cargo redistributions decreased by 22%, which implies a more accurate initial selection of the system when choosing a storage location and, accordingly, reduces further labour costs for moving cargo within the warehouse. This indicator not only optimizes business processes but also reduces the risk of cargo damage. The next efficiency parameter chosen was the coefficient of the density of storage area use, which increased by 9%, indicating the rational use of warehouse areas. The increase in the percentage of this indicator is due to the more thoughtful distribution of cargo within the storage area [23].

Another key performance indicator was the timeliness of priority shipments, which improved by 17%. This increase is largely attributed to the incorporation of the delivery priority parameter and the system's enhanced responsiveness to changes in cargo handling sequences. As illustrated in Figure 7, internal operations within airport cargo terminals have undergone notable optimization. The implementation of the proposed methods and machine learning algorithms has not only enhanced warehouse performance but also contributed to greater overall resilience and efficiency within the logistics network.

4.5.   Discussion of results

As part of this study, a hybrid decision support system for air cargo terminals was developed and tested based on the integration of machine learning methods, AHP, and TOPSIS. Tests conducted in a real warehouse show the high efficiency of the proposed approach, especially in comparison with those used today. The developed machine learning model based on the RFC algorithm demonstrated a high classification accuracy for all generally accepted parameters. The use of the TOPSIS method is necessary to ensure the ranking of possible storage zones, which is important in dynamic and multifactorial warehouse operations [24].

As a result of the work performed, the importance of the physical characteristics of cargo, such as weight and quantity, was confirmed when choosing the optimal place for storing cargo was confirmed. The integration of these factors into the developed system using engineering processing of cargo characteristics allows the selection of a reasonable storage location considering the system's recommendations. Additional consideration of delivery priority, size, and type of cargo ensures the flexibility of the system and gives it the ability to adapt to the changing operating conditions of the cargo terminal. The KPI analysis before and after the implementation of the system showed an improvement in operational indicators: a decrease in cargo processing time by 14%, a decrease in the number of redistributions by 22%, an increase in the efficiency of warehouse areas by 9%, and an increase in the timeliness of shipments of the most priority orders by 17% [25].
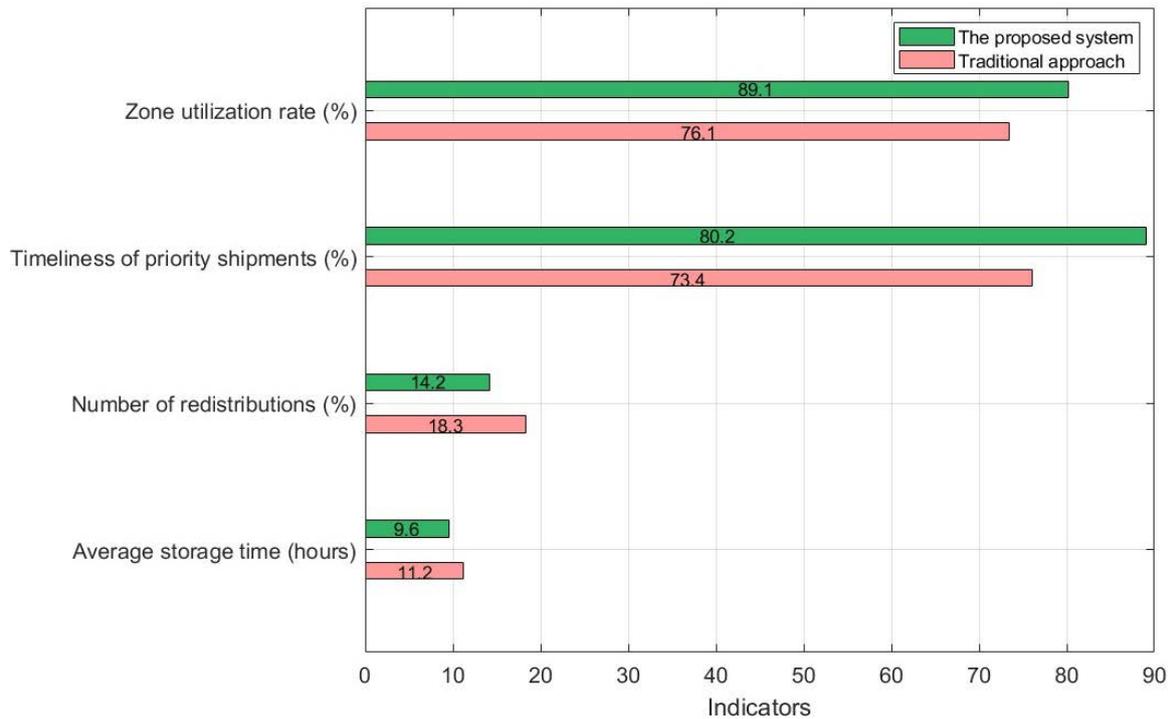
Figure 7 Comparison of the main KPIs before and after the implementation of the system

Several specific limitations in the developed system were observed. The model was trained on data collected at a specific warehouse and set of goods, which limits the universality of the system without adaptation to the conditions of other warehouses. In addition, the developed model does not consider the factors of seasonality and structure of cargo flows in different countries. Removing those restrictions is a subject of future research. Further work will also involve introducing adaptive learning mechanisms into the model as well as establishing a digital twin in the warehouse to be able to perform simulations of different scenarios involving placing groups inside the warehouse.

This study has proven that machine learning and, especially the Random Forest algorithm, can be very effectively applied in the process of optimizing the storage zone classification and improving the work of the warehouse. The Excellent classification accuracy and apparent decrease in cross-zone misclassification confirm the efficiency of the model and allow comparison with the previous researchers [26]. As compared to those previous models, which tended to use clustering methods or rule-based heuristics, the current work proposes a more sophisticated model in that it both uses AHP to weight features and proposes pattern-sensitive handling priorities. Such a combination presents more flexibility and reactivity to real-time operational changes. The noted 17% increase in the punctuality of priority cargo deliveries also speaks of the practicability of the system and its ability to respond to changing conditions. To the academic community, the results of this study unlock the avenues of future research into the hybrid intelligent logistics framework that integrates the decision-making framework with predictive analyses. A combination of explainable decision logic and state-of-the-art classifiers composes a deployable logistics optimization framework [27].

From a practical perspective, this system demonstrates a replicable example to logistics practitioners, especially in high-volume air cargo hubs where space and delivery windows are at a premium. It provides a scale-out solution to enhance throughput, accuracy, and resource utilization. At the policy level, the implementation of such intelligent storage classification systems is quite appropriate in terms of the government programs to increase the national logistics performance rates and upgrade the infrastructure to the level of international smart logistics and digitalization.

4   Conclusion

This research proposes a fully integrated hybrid decision support system that combines machine learning with multicriteria decision-making methods to optimize storage allocation in air cargo terminals. By integrating the RFC with AHP and TOPSIS, the system not only predicts optimal storage zones based on cargo attributes but also incorporates expert priorities to ensure interpretability and operational consistency. The model is trained and validated using 1,500 real-world cargo records from Almaty International Airport, covering diverse operational conditions.

The results show that this hybrid approach significantly enhances warehouse efficiency. Average storage time is reduced by 14%, cargo redistributions are minimized by 22%, space utilization improves by 9%, and on-time delivery for priority shipments increases by 17%. In classification performance, the RFC model achieves an accuracy of 61%,

outperforming SVM (41.5%), Decision Tree (39.0%), and Logistic Regression (37.0%). The use of AHP for deriving feature weights and TOPSIS for ranking storage decisions enables a structured and transparent allocation process aligned with logistical priorities.

However, some limitations are noted. Since the model is trained on data from a single airport, its direct application to other terminals with different cargo types, spatial layouts, or seasonal trends may require retraining or adaptation. Dynamic operational factors like real-time cargo inflow, emergency rerouting, and staffing variability are not yet integrated into the system. Future developments should aim to enhance flexibility through real-time sensor integration, seasonal adjustment capabilities, and reinforcement learning to support adaptive learning. Building a digital twin of the warehouse could further support simulation-based testing and scenario planning. These enhancements would increase the system's practicality, scalability, and strategic value in evolving air cargo logistics environments.

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Abstract: The rapidly growing Moroccan automotive industry faces intense global competition, demanding cutting-edge operational excellence (OpEx). A major challenge lies in understanding and concretely applying the benefits of OpEx in this specific context, particularly concerning flow and supply chain management. This study aims to explore the impact of implementing operational excellence practices on the performance of companies operating within Morocco's automotive sector, specifically identifying the key dimensions that contribute most to this improvement and their implications for competitiveness and logistical performance. To this end, a structured questionnaire was developed and distributed to 264 firms in the industry. The pilot study yielded 246 valid responses, resulting in a response rate of 93%, thereby ensuring a high level of representativeness across the sector. The reliability and validity of the measurement instruments were rigorously assessed, and data analysis was conducted using the statistical software SPSS, version 28. The findings highlight eight core dimensions identified as the most influential drivers of operational excellence in the specific context of the Moroccan automotive industry. Results indicate that the adoption of these practices leads to notable improvements in profitability, customer satisfaction, and organizational responsiveness to market shifts, particularly within logistics operations and the overall supply chain. These insights offer practical guidance for industry stakeholders aiming to strengthen long-term competitiveness and provide a valuable empirical foundation for researchers and practitioners seeking a deeper understanding of the tangible benefits associated with operational excellence in industrial settings, especially regarding logistics management and flow optimization.

1   Introduction

The Operational excellence (OpEx) represents a strategic orientation adopted by automotive companies aiming to deliver superior value in terms of quality, pricing, purchasing convenience, and service standards within their logistics processes and competitive landscape [1]. This approach centers on the integration of lean methodologies, technological innovation, and effective management frameworks to streamline processes, increase operational efficiency, and promote long-term sustainability [2,3]. Structured methodologies such as Lean, Six Sigma, and Total Quality Management (TQM) provide foundational tools and practices that support the pursuit of these efficiency and performance goals [4], notably in logistics and production management.

The growing relevance of operational excellence is particularly evident in emerging industrial ecosystems, such as Morocco's automotive sector, which has undergone significant transformation over the past decade. Between 2017 and 2024, Morocco has experienced a notable progression in global automobile production, marked by consistent growth in both volume and international standing. Based on figures reported by the International Organization of Motor Vehicle Manufacturers (OICA) and interpreted by M. Hamoumi et al. [5], the country advanced from 30th position in 2020 to 24th in 2023 and maintained this rank in 2024, an advancement that occurred over a relatively brief period. This trend is indicative of a deliberate and dynamic industrial policy, bolstered by the presence of leading global automotive firms and the consolidation of a strong domestic supplier network. From 2023 to 2024, Morocco recorded a 4% increase in vehicle production, reaching a total of 559,645 units. This performance places the country sixth worldwide in terms of annual production growth, highlighting its rising significance within the global automotive landscape and reinforcing its role as a key industrial player in the North African region, particularly in terms of logistics and supply chain capabilities. Furthering this discussion, a study by El Affaki et al. [6] provides a roadmap for automotive firms, demonstrating the

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synergistic impact of implementing Lean Management tools in conjunction with the IATF 16949:2016 quality standard to drive operational excellence.

However, this industrial dynamism is accompanied by specific challenges concerning the integration of operational excellence within the Moroccan automotive sector. The optimization of logistical flows and the management of an increasingly complex supply chain represent major stakes. While previous research has examined the outcomes of OpEx in this context, it has often overlooked an in-depth analysis of the close ties between OpEx and logistical performance or has not proposed an empirically validated framework for action specifically adapted to the realities of the local market. It is precisely this gap that our study seeks to address: how can the concrete application of operational excellence practices transform the performance of Moroccan automotive companies, specifically targeting their logistical dimensions and overall competitiveness? Our primary objective is therefore to build a detailed understanding of the mechanisms by which operational excellence generates a direct and measurable impact on logistical performance and the overall competitiveness of the automotive sector in Morocco.

The scientific contribution of this work lies in its integrated approach, which enriches the operational excellence model with a deep logistical perspective, validated by a rigorous empirical methodology covering 93% of the Moroccan automotive market. From a practical standpoint, this study offers companies a concrete and proven roadmap. This guide, informed by reliable local data, aims to help them optimize their operations and strengthen their position in the global market.

This study outlines a methodological approach for developing a tailored operational excellence model, grounded in the specific characteristics of the Moroccan market and informed by the latest advancements in management practices. While previous research has largely focused on assessing the outcomes of operational excellence within Morocco's automotive industry, this study takes a more comprehensive perspective, integrating the role of logistics elements. By analyzing data representing 93% of the national automotive sector, the research highlights tangible benefits linked to operational excellence, particularly in terms of productivity, product quality, and customer satisfaction, which are inherently tied to efficient material flows and distribution logistics. It also identifies the key drivers that enable firms to streamline their operations and enhance competitiveness, especially in logistics and manufacturing. Ultimately, this study provides Moroccan automotive companies with a practical and evidence-based roadmap for strengthening their position in the global market through the implementation of a proven operational excellence framework, with a focus on optimizing logistical processes.

2 Literature review
2.1 The Operational Excellence

Excellence is widely used in research and practice, yet many organizations struggle to achieve it due to confusion among managers regarding its meaning [7]. The Operational Excellence (OpEx) is achieved through high-performance teams seeking continuous improvement in well-designed processes, using appropriate tools and technologies [8]. It is underpinned by a philosophy that combines problem-solving, teamwork, and effective leadership, focusing on customer needs and empowering employees to maintain optimal value flows, including logistics flows [8]. OpEx is often used as a desired goal, but its meaning is ill-defined, necessitating a comprehensive review to clarify its theoretical foundation [9].

A range of methodologies and frameworks are utilized to support the achievement of operational excellence, each offering distinct yet often complementary approaches. Lean Management emphasizes the elimination of waste and the enhancement of process efficiency, particularly in production and logistics processes [10], while Six Sigma provides a data-centric methodology focused on minimizing defects and reducing process variability [11,12]. Total Quality Management (TQM), on the other hand, adopts a holistic perspective by engaging all organizational levels in continuous quality improvement efforts [12,13]. Business Process Orientation (BPO) explores the impact of process-centric thinking both within and across organizational boundaries to improve overall performance [14]. Hoshin Kanri offers a strategic alignment mechanism that integrates long-term sustainability objectives with operational performance goals [15]. These approaches are not mutually exclusive and are frequently implemented in combination, such as in Lean Six Sigma, which merges Lean's process efficiency principles with Six Sigma's rigorous data analysis, to create a comprehensive and synergistic path toward operational excellence [12], particularly beneficial for supply chain management and logistics optimization.

2.2 Benefits of Operational Excellence

Operational Excellence, frequently implemented through methodologies such as Lean Six Sigma, provides significant advantages to businesses. In-depth studies, particularly within the automotive sector, have demonstrated its positive impact on the overall performance of companies. Organizations that embrace this concept derive notable benefits across various areas, including logistics performance:

Financial Performance: The research of [16] alongside that of [17] indicates that Operational Excellence significantly improves the return on assets by reducing expenditures, particularly indirect costs. Logistics cost reduction is often a key

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contributor. [18] corroborate these findings by highlighting the favorable impact on key performance indicators such as the rate of defects per unit produced.

Operational Performance: Operational Excellence leads to the optimization of production and logistics processes. [19-21] highlight substantial reductions in cycle times, inventory levels, and downtime, while simultaneously increasing overall production capacity and improving material flow management.

Customer Satisfaction: By diminishing imperfections and delivery lead times, Operational Excellence enhances the quality of the products or services offered, which in turn results in improved customer satisfaction, as demonstrated by the studies of [19,20]. This is directly linked to efficient distribution logistics.

Business Strategy: Operational Excellence integrates seamlessly with the overall business strategy, as emphasized by [17,22]. It contributes to strengthening the organization's competitiveness by aligning operations with defined strategic objectives, encompassing logistics strategy.

Human Resources: Operational Excellence fosters a constructive work environment. [18,23,24] underscore the importance of employee engagement, continuous training, and a culture centered on ongoing improvement, vital for managing human flows and ensuring logistics operations run smoothly.

More recent research, such as that by [25,26], broadens the scope of Operational Excellence to encompass new sectors and challenges. [25] sheds light on the positive influence of Lean Six Sigma on the performance of Indian manufacturing industries, while [26] notes the increasing interest in Operational Excellence within the energy sector. These works illustrate the evolution of practices and the continuous adaptation of improvement methodologies to address the specific issues of each field, including logistics issues.

Investigations conducted within the automotive industry consistently affirm the effectiveness of the Lean Six Sigma approach in this sector. The studies by [27] demonstrate how the combination of Lean tools and the DMAIC methodology enables improvements in quality, productivity, and customer satisfaction in the manufacturing of automotive components, optimizing logistics and production flows. [28] propose a Lean Sigma framework tailored to the specific characteristics of manufacturing companies, illustrating its benefits in terms of cost reduction and quality enhancement, particularly for manufacturing logistics. [29] offer a specific contribution by suggesting solutions to minimize the loss of electronic components during assembly, which also impacts material flow and inventory management.

In conclusion, the entirety of this research establishes that Operational Excellence is a powerful lever for optimizing the overall performance of a company, whether in terms of financial results, operational efficiency, customer satisfaction, strategic alignment, or the development of human capital. The benefits are numerous and impact all dimensions of the organization, including logistics functions and the supply chain.

3 Methodology

This research was conducted using a quantitative approach, favoring a survey methodology to collect primary data from stakeholders in the Moroccan automotive sector. The process began with the meticulous development of a structured questionnaire, designed to capture perceptions and practices related to operational excellence. This questionnaire was pre-tested with a small sample of professionals to refine its clarity and relevance. Subsequently, data collection was systematized: the questionnaire was directly distributed to the 264 identified companies, ensuring comprehensive sectoral coverage. This meticulous deployment allowed us to obtain a substantial number of 246 usable responses, reflecting an exceptional response rate of 93%, guaranteeing a high representativeness of the sample. The raw data collected was then carefully verified and prepared for statistical analysis, primarily focused on regression techniques, to uncover the relationships between operational excellence variables and performance indicators.

3.1 Research framework and data analysis

This research provides a comprehensive mapping of the Moroccan automotive sector. It establishes a complete inventory of key players, ranging from major international manufacturers such as Renault and Stellantis to the leading independent Moroccan manufacturer, Neo Motors, without omitting the entire subcontracting network. By examining the data of 264 companies identified on December 2024, this analysis offers a clear perspective on the operations, origins, and geographical distribution of each actor, thereby enriching the understanding of the organization and dynamics of this essential sector for the Moroccan economy, particularly in terms of supply chain structure and logistical network.

The Moroccan automotive sector is characterized by a vibrant interaction between international players and domestic companies. Foreign firms, mainly French, American, and Japanese, constitute 68% of the industrial fabric, bringing their expertise and advanced technologies, which often include sophisticated logistics systems. As for Moroccan companies, although fewer in number, they play a fundamental role in the diversification of the sector and in innovation. Joint ventures, such as those uniting Induver and AGC or Tuyauto and Gestamp, are catalysts for growth, encouraging the transfer of technologies and access to global markets. This mix of national and international actors contributes to the competitiveness and dynamism of the Moroccan automotive industry, affecting its logistics performance and global trade flows.

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3.2 Research sample characteristics

The examination of the sample reveals a characteristic profile of actors in the Moroccan automotive industry, where a significant proportion works in technical sectors such as engineering, production, and quality control, often involved in logistics and material handling. The younger generation, particularly those aged 20-30, represents a significant part of the workforce, contributing through their energy and receptiveness to new technologies, including those used in transport and information management systems within logistics. Nevertheless, the experience of more seasoned professionals (with more than five years of seniority) remains a considerable advantage for ensuring the transmission of skills and the continuity of businesses, especially in complex logistics operations. The distribution of hierarchical levels also illustrates this dynamic: although managers and technicians are the most numerous, leaders are also present, highlighting the importance of strategic decision-making within the sector.

The survey highlights a structure where technical functions occupy a central place. This predominance aligns with the current challenges of the automotive industry, which demand specialized expertise in design, manufacturing, and quality assurance, as well as efficient logistics and distribution networks. The harmonious presence of young talent and experienced professionals fosters a stimulating and innovation-friendly work environment. The conclusions of this analysis underscore the need to maintain this balance to ensure the long-term competitiveness of the Moroccan automotive sector, particularly through improved logistics and operational efficiency.

Table 1 Demographic and professional composition of the research sample

Characteristics	Result	Percentage
Function	Engineering	26%
	Production	24%
	Quality	20%
	Maintenance	12%
	Human Resources	6%
	Method	6%
	Finance	3%
	Purchasing	3%
Hierarchical Level	Executive, Member of the Executive Committee	8%
	Supervisor	12%
	Manager	39%
	Technician	21%
	Team Leader	16%
	Operator	4%
Age	20-30	62%
	30-40	31%
	40-50	6%
	+50	2%
Professional Experience	Less than 2 years	28%
	2 to 4 years	30%
	More than 5 years	43%

3.3 Identification and selection of operational excellence attributes

The various benefits of Operational Excellence were identified through a literature review, using keywords such as "advantages of Operational Excellence", "attributes of Operational Excellence", "logistics performance", "supply chain efficiency" and by consulting databases like Google Scholar and Scopus. A total of 17 attributes were selected in collaboration with experts in the field.

3.4 Instrument reliability test

The reliability analysis was conducted using IBM SPSS Statistics 28 software. The consistency of the collected data was verified, and Cronbach's alpha coefficient was estimated at (0.727), which is considered satisfactory for the study. This proves that the research instrument used is reliable and consistent in data collection. Therefore, if a research instrument consistently assesses the desired traits, it is considered reliable. Each research instrument used in this study successfully passed the reliability tests, presenting Cronbach's alpha values greater than 0.7. This attests to the reliability of each research instrument, indicating that the questionnaire can be used. The results of the reliability tests are presented in Table 2.

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Table 2 Reliability test results for the research instrument

Theme	Variables	Measurement Instruments and Coding	Cronbach's Alpha if Item Deleted
Attributes	Financial Performance	**AT01**_Boosting Profitability	0.717
		AT02_Cutting Costs	0.718
		AT03_Streamlining the Supply Chain	0.714
	Operational Performance	**AT04**_Upping Productivity	0.704
		AT05_Optimizing Processes	0.712
		AT06_Slashing Waste and Environmental Impact	0.711
		AT07_Trimming Downtime	0.718
	Customer	**AT08**_Elevating Customer Satisfaction	0.710
		AT09_Enhancing Product/Service Quality	0.716
		AT10_Shortening Delivery Times	0.707
		AT11_Building Customer Loyalty	0.720
	Strategic	**AT12**_Sharpening Competitiveness	0.724
		AT13_Better Navigating Market Shifts	0.714
		AT14_Developing New Offerings	0.720
	Human Resources	**AT15**_Boosting Employee Morale	0.720
		AT16_Skill Development	0.720
		AT17_Increasing Employee Engagement	0.713

3.5   Model development

The research model for this study was developed with the assistance of experts in the field. To develop the model, 17 attributes of Operational Excellence were considered as independent factors, and the benefits of Lean Six Sigma implementation were considered as a dependent factor, taking into account their impact on logistics performance. The research model for this study is presented in Figure 1.
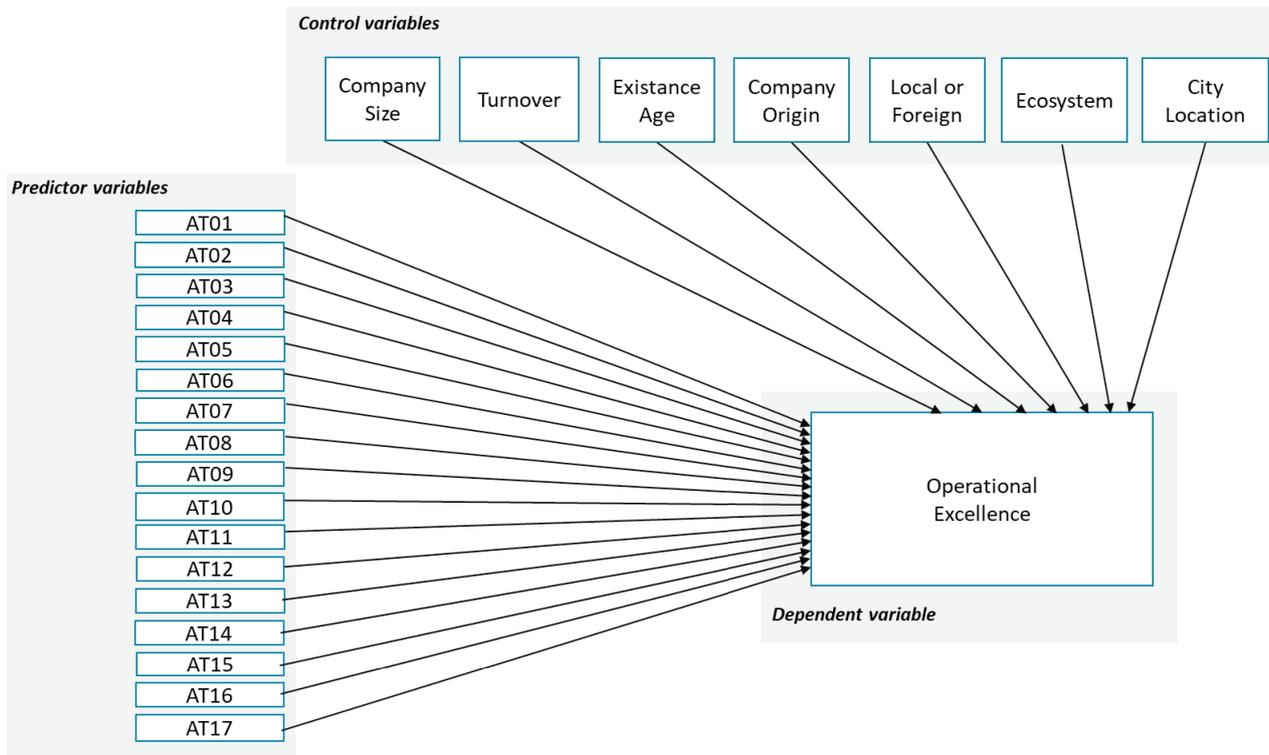
Figure 1 Developed Research Model

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4 Results

4.1 Hypothesis testing

Hypothesis testing is performed using regression analysis. The analysis is conducted using IBM SPSS Statistics 28 software.

Table 3 Reliability test results for the research instrument

Independent Variables	Std. coeff. β	p-value
AT01_ Increased Profitability	0.133	0.007
AT02_ Cost Reduction	0.133	0.002
AT03_ Supply Chain Optimization	0.175	0.000
AT04_ Increased Productivity	-0.019	0.694
AT05_ Process Optimization	0.106	0.017
AT06_ Waste and Environmental Impact Reduction	0.005	0.902
AT07_ Downtime Reduction	0.054	0.164
AT08_ Increased Customer Satisfaction	0.033	0.472
AT09_ Improved Product/Service Quality	0.072	0.075
AT10_ Reduced Delivery Times	-0.037	0.420
AT11_ Increased Customer Loyalty	0.053	0.175
AT12_ Increased Competitiveness	0.085	0.030
AT13_ Better Adaptation to Market Changes	0.107	0.010
AT14_ Development of New Products/Services	0.102	0.008
AT15_ Improved Employee Morale	0.007	0.869
AT16_ Skills Development	0.053	0.193
AT17_ Increased Employee Engagement	0.100	0.021

The increase in profitability, cost reduction, supply chain optimization, process optimization, increase in customer satisfaction, improvement in the quality of products/services, reduction in delivery times, increase in competitiveness, better adaptation to market changes, development of new products/services, and increase in employee engagement are all strongly associated with an improvement in the dependent variable. This indicates that these attributes significantly contribute to operational excellence, encompassing logistics performance.

The increase in productivity, reduction of waste and environmental impact, reduction in downtime, increase in customer loyalty, skills development, and improvement in employee morale do not appear to have a significant impact on the dependent variable, according to the results of this analysis.

In summary, the results highlight the importance of several classic attributes of operational excellence such as cost reduction, quality improvement, and adaptation to market changes. However, it is interesting to note that some attributes like increased productivity and waste reduction, although often associated with operational excellence, do not seem to have a significant impact in this particular context.

4.2 Control variables

The regression analysis conducted to test the influence of several control variables on Operational Excellence (OpEx) reveals a mixed set of results: while company size ($p = 0.055$) and company origin ($p = 0.460$), ecosystem ($p = 0.814$), and city location ($p = 0.147$) did not show statistically significant relationships with OpEx, turnover ($p = 0.003$), age of existence ($p < 0.001$), and whether the company is local or foreign ($p = 0.001$) did demonstrate a significant impact, suggesting that higher turnover, a longer history of operation, and being a local versus a foreign entity are associated with greater levels of Operational Excellence within the studied context, possibly due to existing logistics infrastructure or specific material flow characteristics.

Table 4 Research hypothesis testing for "Control Variables"

Research Hypothesis Test	Statistical Result t/f	p-value	Result
Company Size -> OpEx	1.92	0.055	Not Supported
Turnover -> OpEx	2.99	0.003	Supported
Age of Existence -> OpEx	4.24	0.000	Supported
Company Origin -> OpEx	0.74	0.460	Not Supported
Local or Foreign -> OpEx	3.37	0.001	Supported
Ecosystem -> OpEx	0.24	0.814	Not Supported
City Location -> OpEx	1.45	0.147	Not Supported

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The study highlighted that company size, turnover, and age are factors significantly associated with better operational performance. Furthermore, foreign companies also appear to benefit from a slight advantage in terms of operational excellence, potentially due to their established global logistics networks and technical logistics elements. Conversely, the company's origin, its ecosystem, and its geographical location do not seem to have a significant impact on the results. Although the statistical model used explains a significant portion of the variability in operational excellence, it is important to note that other unmeasured factors could also play a role, such as specific transportation infrastructure or information flow management practices. In conclusion, the results of this analysis reveal that operational excellence is closely linked to several organizational factors. Indeed, our findings suggest that larger companies with substantial turnover and a longer history are better able to implement operational excellence practices, including advanced logistics management strategies. However, it is important to note that this study does not establish causal relationships, and other unmeasured factors could also influence the results.

5   Discussion

The findings of this study align with the broader literature on Operational Excellence (OpEx), as highlighted by [16,17], which emphasize the positive impact of OpEx on financial performance, particularly through cost reduction, a key attribute found significant in the Moroccan automotive context, notably logistics cost reduction. Similarly, the observed improvements in customer satisfaction resonate with [19,20], who linked OpEx to enhanced product/service quality and reduced delivery times, although the latter was not statistically significant in this specific study, perhaps due to factors within distribution logistics. The study's identification of supply chain and process optimization as significant drivers of OpEx echoes the focus on process efficiency found in Lean Management [10] and the defect reduction focus of Six Sigma [11,12]. Interestingly, while prior research [18,23,24] underscores the importance of human resource factors like employee engagement and skills development, these attributes did not show a significant direct impact on OpEx in this Moroccan automotive sample, suggesting a potential contextual difference or the influence of mediating factors not explored in this research, possibly related to human flows within logistics operations. Furthermore, the significant role of organizational factors like company turnover and age in facilitating OpEx implementation suggests that the capacity to invest in and sustain OpEx initiatives may be linked to the maturity and financial health of the firms, a nuance that could be further explored in future research building upon the foundational understanding provided by this study, particularly regarding their logistics capabilities.

This study advances the academic position that the effectiveness of operational excellence is not a universal constant, but is instead deeply tied to a specific industrial and organizational context. In contrast to some prior research that assumes a general impact from all OpEx attributes, the present findings indicate that, within the Moroccan setting, certain elements like improved productivity or reduced waste are not the primary drivers of performance. This observation enriches the academic body of knowledge by highlighting the need for a more nuanced, contextual approach, challenging the blind application of standard OpEx models. For practitioners, the implication is direct: efforts should be concentrated on specific dimensions, such as supply chain optimization and cost reduction, which are shown to generate a measurable impact. As for government policymakers, these conclusions suggest that support for the automotive industry should favor operational excellence strategies that are tailored to local specificities, particularly in logistics and the development of national supplier networks, in order to maximize returns and strengthen the sector's overall competitiveness.

6   Conclusion

This study has demonstrated that the adoption of operational excellence practices has a positive impact on the performance of Moroccan automotive companies. By surveying nearly 246 businesses, representing a broad cross-section of the sector, it was established that those that have implemented continuous improvement practices generally experienced more sustained growth. These companies have successfully optimized their processes, reduced their costs, and improved the quality of their products and services, which has allowed them to strengthen their competitiveness and better satisfy their customers, largely through efficient logistics and supply chain management.

While increased profitability, customer satisfaction, and agility in the face of market changes are undeniable benefits of operational excellence, our results suggest that not all aspects of this approach have the same impact. Indeed, while cost reduction and quality improvement are essential drivers, other factors such as waste reduction or increased productivity appear less decisive in the specific context of the Moroccan automotive industry, perhaps due to the existing logistics network or specific transportation challenges.

The analyses also revealed that the successful implementation of operational excellence is closely linked to certain organizational factors. Larger companies, with greater resources and a longer history, appear better equipped to carry out such initiatives, often possessing more developed logistics infrastructures and expertise in material management. Furthermore, the duration of implementation, the visibility of the results obtained, and the commitment of a dedicated team are key elements to ensure the success of these projects, including those focused on logistics process optimization.

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In summary, the findings substantiate the research's core hypothesis: operational excellence serves as a significant performance driver for the Moroccan automotive sector, though its impact is shaped by the specific context of each company and its logistical capacities.

7 Limitations and future directions

This study has demonstrated the benefit of operational excellence for Moroccan automotive companies, while also highlighting the need for a personalized approach adapted to the specific context of each company, including its logistics particularities. A key challenge encountered was the cross-sectional design of the survey. While this approach ensured broad coverage, it precluded an in-depth case study, limiting the ability to analyze the internal dynamics of OpEx in detail. Furthermore, the reliance on self-reported data from companies may introduce a potential for perception bias. Though the validity and reliability of the instrument were tested, these limitations should be considered when interpreting the results. The results obtained open interesting avenues for future research, particularly by exploring the impact of operational excellence on other sectors of activity or by analyzing the cultural and organizational factors that can promote or hinder its adoption, especially concerning supply chain integration and logistics innovations. Future work could also involve conducting longitudinal studies to assess the long-term evolution of OpEx practices' impact. Alternatively, more targeted case studies could be undertaken to understand the factors driving success or failure in implementing OpEx within specific firms, thereby enabling a more detailed analysis of their logistical processes and associated infrastructure.

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Driving performance: benefits of operational excellence in the automotive industry
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Optimisation of wind park location

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Keywords: wind parks, location models, multi-criteria evaluation of variants, PROMETHEE II.
Abstract: The development of wind farms within each country's energy system is a significant step towards reducing greenhouse gas emissions and enhancing energy security. Given Slovakia's high potential for wind energy and the limited exploitation of this resource, this study conducted a multi-criteria analysis of factors influencing decisions on the location of wind farms. The effective integration of this renewable source requires optimized planning and management of material, information, and investment flows, which are key elements of logistics management in the construction and operation phases of wind farms. The correct location of wind farms requires an analysis of several logistical and technical elements, such as infrastructure availability, transport flows, energy flows, information flows, legal and environmental constraints, as well as wind conditions (e.g., average wind speed, wind energy density). The PROMETHEE II method was used to assess potential sites, allowing for the comparison of alternatives based on preference flows. The output of the analysis is a map of the logistical suitability of different locations, along with a ranking of areas derived from net flow calculations (location-based logistics). The findings of this study can contribute to the effective management of logistics processes in the renewable energy sector, as well as to better management of investment, information, and material flows in the construction of wind farms in Slovakia.

1   Introduction

In general, sustainable development makes it possible to meet the needs of present generations without compromising the demands of future generations to meet their needs. The United Nations has articulated global priorities for achieving sustainable development in the 2030 Agenda (endorsed by the UN General Assembly in September 2015, https://sdgs.un.org/2030agenda). The 2030 Agenda sets out 17 Sustainable Development Goals (SDGs) elaborated into 169 related sub-goals to guide the structural political, economic, and social transformation of countries around the world. It expresses the intention of countries to guide their development towards sustainability and to set their national policies, strategies, and planning to contribute to the achievement of the global goals.

The overall economic development of any country is dependent on high energy consumption, which is why the 2030 Agenda is also paying increased attention to measures to increase the use of renewable energy sources in order to reduce greenhouse gas emissions. Although the share of renewable energy in the energy mix has been increasing in recent years (although fossil fuels still remain the basis of the energy mix), it is essential that countries implement green policies and comply with the targets set in their national energy climate plans.

Slovakia has long been below the EU average in the use of renewable energy sources (RES), including wind energy, with RES accounting for 23% of final energy consumption, according to data from OKTE [1]. One of the challenges to increase the share of RES in final energy consumption is the robust use of wind energy. This is to be ensured by legislative at the European Union level (Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources) as well as at the national level (Act No. 251/2012 Coll. on Energy and on Amendments to Certain Acts, as amended, Act No. 309/2009 Coll. on the Promotion of Renewable Energy Sources and High Efficiency Combined Generation and on Amendments to Certain Acts, as amended).

As one of the most promising renewable energy sources, wind energy offers significant potential to promote energy security and reduce greenhouse gas emissions. Although wind energy has some disadvantages (e.g., its instability, impact on the landscape, risk of bird deaths, etc.), its advantages are very high (e.g., the cheapest source of electricity, environmentally friendly, reduced dependence on fossil fuels, etc.). The reality is that more clean and renewable energy

sources are now needed in light of sustainable development policies. Unlike energy produced from non-renewable sources, wind energy cannot be depleted, and its production does not pollute the environment.

Despite the fact that Slovakia does not have the same conditions for the implementation of wind energy in its energy mix as some other European countries, the appropriate deployment of wind farms can ensure the efficient use of available resources.

The most important determinants for the efficient use of wind energy are mainly financial incentives, a stable regulatory framework, but also the identification of optimal locations for wind power plants [2].

The structure of the work is based on the implementation of a sequence of steps. Following the introduction and a brief literature review, the third methodological part focuses on eliminating unsuitable locations for wind farms based on geographical and legislative requirements. The criteria for determining the suitability of sites for wind farms in the Slovak Republic are also formulated in the third part. The method of evaluating individual criteria for eliminated sites is described in the methodological part. The actual application of wind farm location in the Slovak Republic based on the PROMETHEE II method is described in the fourth part. The result of the solution is a ranking of wind farm sites in each area based on the calculated net flow values, and this approach is presented in the discussion on the general procedure for solving decision-making problems related to the location of wind farms. The results achieved are evaluated in the conclusion.

2   Literature review

Effective location of wind farms plays a key role in reducing costs, optimizing revenues, and minimizing negative impacts on the population and the environment (e.g., [3-5]). Currently, there is a relatively large number of contributions devoted to this topic, many of which focus on linking multi-criteria decision-making methods and geographic information systems (GIS) as tools for acquiring, analyzing, visualizing, and managing data with spatial or map representation.

Sotiropoulou, et al. [6] presented a hybrid model for selecting suitable locations for the construction of onshore wind farms in northeastern Greece, which combines AHP (Analytic Hierarchy Process): used to determine the weights of individual criteria in multi-criteria decision-making, PROMETHEE II: used for the final ranking of alternatives (sites) based on calculated preference flows, Machine learning – kNN (k-Nearest Neighbors) and SVM (Support Vector Machines): used for regression analysis of spatially specific inputs, in particular for modeling and interpolating wind potential in areas with limited measurements. Josimović, et al. [7] applied a two-phase location selection model in which GIS removed unsuitable areas and PROMETHEE II subsequently evaluated the remaining sites. Their methodology enabled transparent selection of sites for wind farms by legislative and planning requirements. Latinopoulos and Kechagia [8] used a combination of AHP-GIS to locate wind farms in Greece, highlighting the advantages of a weighted approach to spatial criteria such as distance from settlements, protected areas, altitude, and wind speed. Al-Yahyai, et al. [9] analyze the possibilities and limitations of wind prediction models in wind farm planning.

Although location-based logistics methods are often used in the localization of wind farms, combined approaches based on GIS and Multi-Criteria Decision-Making methods (MCDM) [10-14] are increasingly being used, which allow for the analysis of areas in terms of technical, environmental, logistical, and socio-economic criteria. The PROMETHEE II method from the MCDM category was used in the analysis of wind farm locations, and examples of its successful application in various areas include: [15,16]

• Evaluation of economic regions [17]: Using the PROMETHEE II method, the economic indicators of the different regions were evaluated to identify the areas with the best performance.

• Hospital evaluation [18]: In the health care sector, the PROMETHEE II method was used to evaluate the performance of public hospitals, which helped to identify areas for improvement.

• Transportation Planning [19]: evaluating roadway alternatives.

• Selecting investment projects [20]: a multi-criteria assessment of returns.

• Environmental decision making [21]: evaluating ecological impacts.

In recent years, the PROMETHEE II method has been further developed and applied in various fields:

• Sustainability Assessment of Renewable Energy in Morocco [22]: The March 2023 study used the PROMETHEE II method to assess different renewable energy technologies in Morocco. The results showed that solar PV is the most sustainable technology, followed by wind power, hydropower, CSP, and biomass.

• Integration of PROMETHEE II with DEA for assessing the efficiency of water services in Malaysia [23]:

The 2023 study combined the PROMETHEE II method with efficiency analysis using DEA to assess and fully rank the efficiency of water services in 14 states in Malaysia. The results showed that this combination provides a complete and reliable efficiency ranking.

The literature shows that combining GIS tools with PROMETHEE II is an effective way to identify optimal locations to maximise revenues and minimise environmental and logistical costs.

3   Methodology

3.1   Elimination areas

3.1.1   Geographical location requirements

The International Electrotechnical Commission (IEC, https://webstore.iec.ch) standardises the issue of wind turbines in its standard IEC 61400 (https://webstore.iec.ch/en/publication/31267) and classifies turbines according to the wind conditions for which they are designed. These standards are elaborated in the directive of the Ministry of the Environment of the Slovak Republic "Standards and limits for the siting of wind power plants and wind parks in the Slovak Republic", where the legislative criteria are divided into three main groups:

Category A Limits - Areas suitable for development. These are areas with potential for wind energy where there are no significant environmental or legal constraints, they may include lowlands, uplands, mid-mountains and areas with Grade 1 nature conservation designations, they exclude: Residential areas; Protected areas with Grade 3, 4 and 5 nature conservation designations; Protected areas with Grade 3, 4 and 5 nature conservation designations. Areas of wetlands, UNESCO sites and biosphere reserves of European importance; Areas designated for the performance of tasks of the Ministry of Defence of the Slovak Republic; Protection zones of airports and aviation facilities; Protection forests and forests of special designation; Water resources - protection zones I. Protection zones of natural healing and mineral resources of the I. degree; Spa places and natural healing spas, where laws prohibit other uses; Cultural monuments and protection zones of the UNESCO World Heritage List; Mining areas and areas with permit for mineral extraction; Protection zones of linear objects - roads and highways, railways, electric power lines, gas pipelines, product pipelines, nuclear facilities, burial grounds and crematoria

Category B Limits - Areas conditionally suitable for development. These are areas that require further research and the establishment of more stringent criteria, which include protected areas up to the 2nd degree of protection, zones D of protected areas, sites with the occurrence of protected species of birds and bats, the surrounding areas of tourist centres, lazos, archaeological sites, are thus excluded: areas of forests and the surroundings of watercourses; areas with good quality agricultural soils (bonitated units 1. to 4. Groups 1 to 5); Areas designated for the tasks of the Ministry of Defence of the Slovak Republic; Areas of European importance without 3rd to 5th degree of protection; Forest stands and areas within 50 m from the border; Areas of protected landscape areas; Biocentres and biocorridors of local, regional and supra-regional ecological stability; Surroundings of watercourses and areas up to 100 m and hydric biocorridors up to 200 m; Tourism regions of category I or higher; Areas outside the protection zones of airports and their facilities.

Category C Limits - Areas unsuitable for development. These include the surroundings of residential zones, national parks and protected areas with high levels of protection (3rd, 4th and 5th level), animal migration routes, areas with rare birds, cultural monuments, UNESCO sites, protection zones of airports and spas, thus are excluded: protected areas with 2. Protected areas, important bird territories and areas of migration routes; Surroundings of supra-regional hydric bio-corridors and important tourist centres; Tourism regions of national importance and surroundings of linear constructions with safety risks; Territories outside the protection zones of airports and areas of avalanche settlements; Archaeological sites and quiet areas with potential for cultural heritage protection; Protected water supply areas, water resource zones and natural healing resources; Areas climatically suitable for healing, spas and natural healing baths; Areas in visual contact with cultural, historical and landscape landmarks; Agricultural and forest areas with land reclamation measures and woody vegetation; Protected deposit areas, exploration areas and geopark areas.

This logically implies the requirement to identify those areas that are determined by the limits mentioned above. The priority limits were primarily large protected areas and national parks, but also small protected areas and protected bird areas. This implies the elimination of the areas shown in Figures 1 and 2 (the area of the Slovak Republic is 37.49% covered by protected areas).
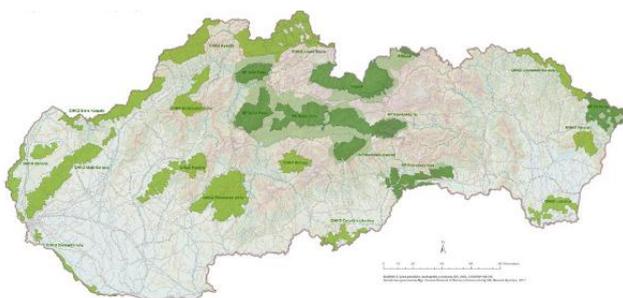
Figure 1 Map of large protected areas, source: [24]

Figure 2 Map of bird protected areas, source: [25]

Geographical conditions, i.e. mountains and forests, can be considered as other important boundary conditions for the location of wind parks, as they represent a serious obstacle to air flow. These thermal boundary conditions are shown in Figures 3 and 4.

Figure 3 Map of mountain ranges, source: [26]
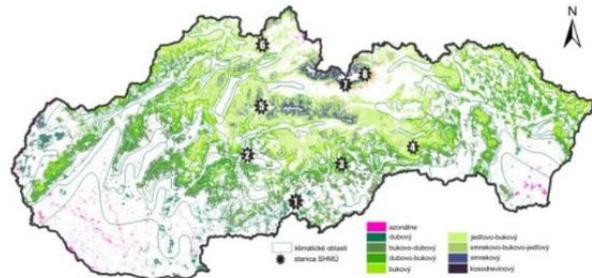
Figure 4 Map of forests, source: [27]

By intersecting the boundaries from Figures 1 to 4, Figure 5 determines a map of suitable areas based on geographical conditions, on which the locations where the legislation allows wind farms to be built are marked.
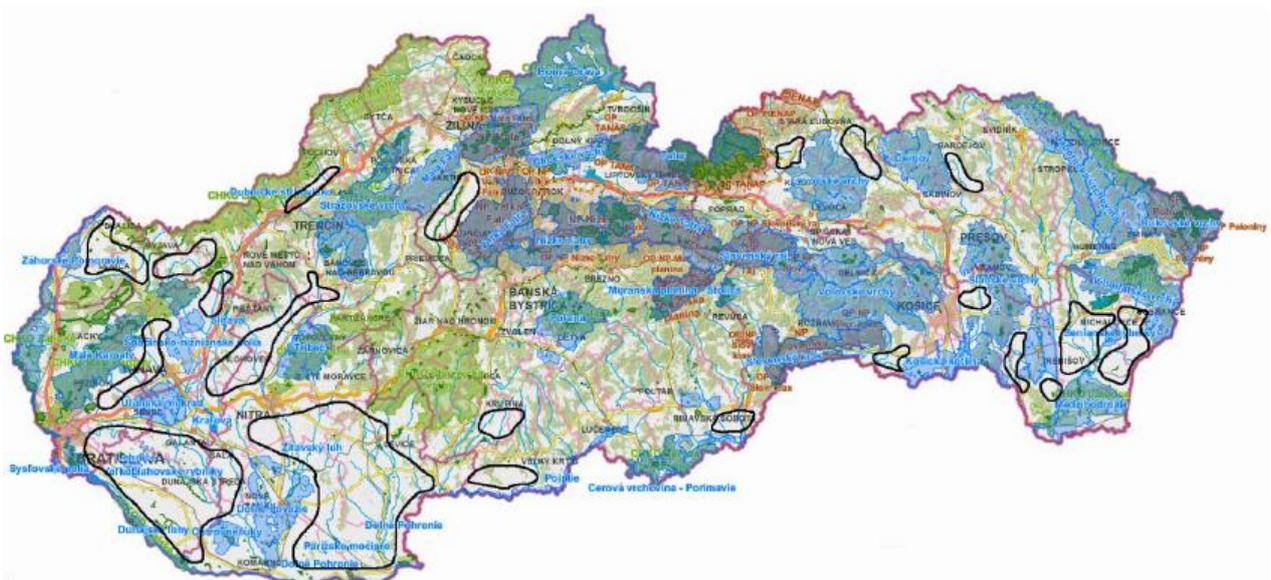
Figure 5 Map of suitable areas based on geographical conditions, source: [26]

3.1.2 Wind location requirements

One of the most important determinants of wind farm location is the average annual air velocity. This is because the output of wind turbines is directly proportional to the third power of the wind speed, with the result that even a small increase in wind speed significantly increases electricity production. Ideal locations are those where the airflow is stable and values between 4 and 25 m/s are usually measured. At lower wind speeds, wind turbines may be switched off or produce less power, at extremely high wind speeds (e.g. above 25 m/s) the turbines may be switched off for protection (depending on the type of turbine installed). A minimum wind speed of 4 m/s is required for efficient operation of a wind turbine, with economic viability being achieved at wind speeds of around 6 m/s. Figure 6 illustrates the different wind speed levels within the Slovak Republic. Figure 6 shows that the strongest airflow can be observed in western and eastern Slovakia and also on the tops of the mountains. These regions have the most stable wind conditions with the highest measured airflow values, which allows wind turbines to operate more efficiently. Although the flow in the northern mountain areas is very strong, the measured values are often too high or irregular, which can limit their suitability for wind turbines.

Another important determinant of wind farm siting is the average wind energy density; this physical quantity is used to describe the energy available in the wind per unit area and is closely related to air density, as air density affects power density. A key characteristic of power density is that it is very sensitive to wind speed, as power increases with the third power of the wind speed, i.e. if the wind speed doubles, power density increases eightfold. A map of the average power density within the Slovak Republic is shown in Figure 7.

Based on the geographical and wind requirements for the location of wind farms, areas can be created that meet all conditions.
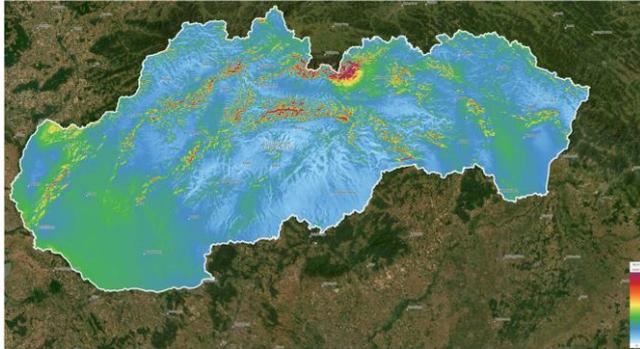
| *Figure 6 Wind speed map, source*: [28] | *Figure 7 Map of average wind energy density, source*: [28] |
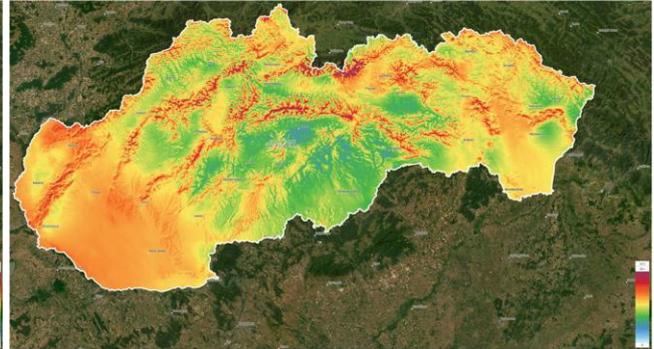
3.2 Criteria for determining the suitability of sites for the construction of wind parks

The selection of suitable sites for wind farms is based on geographical and socio-economic factors. Optimal siting of wind farms has an impact on the efficiency of generation, minimising the cost of electricity generation and transport and reducing the environmental impact of electricity generation and transport. Wind turbines are designed for wind speeds between 3 and 30 m/s, as higher wind speeds could damage the turbine. Therefore, the areas with the greatest potential for the efficient use of wind energy have been identified.

The following decision criteria can then be considered for the identified areas:

1. Wind speed (m/s): Wind speed is a key factor in the selection of sites for wind turbines because it directly affects the amount of energy generated, i.e. because higher average wind speeds increase the efficiency of electricity generation, thus improving the economic return on the project. Meanwhile, the IEC Standards for Wind Turbines distinguish 4 classes of turbines based on this factor:
   a) High Wind Class for areas with high average wind speeds up to 10 m/s,
   b) Medium Wind Class for areas with medium wind speeds up to 8.5 m/s,
   c) Low Wind Class for areas with low average wind speeds up to 7.5 m/s
   d) Very Low Wind Class for areas with extremely low wind conditions below 6 m/s.
2. Average wind energy density (W/m^2): This variable is dependent on the wind speed variable, and if only wind densities greater than 300 W/m^2 are considered for efficiency reasons, the wind strength classification is given as excellent for wind strengths between 6.89 and 7.35 m/s with an average wind power density of 287.19 - 344.62 W/m^2, as excellent for wind strengths in the range 7.35 - 8.04 m/s with an average wind power density of 344.62 - 459.50 W/m^2, and as great for wind strengths in the range 8.04 - 10.80 m/s with an average wind power density of 459.50 - 1148.75 W/m^2.
3. Terrain shape - elevation (m) and slope (degrees): The roughness or height of the terrain also influences turbulence and wind direction, and the construction of wind farms and the economic costs of their operation are lower in the lowlands.
4. Distance from protected areas - NP, SPA, Natura2000, protected bird areas (km): proximity to protected areas is an important environmental aspect.
5. Distance of other limiting elements - surface water, airstrips, power lines (km): other environmental and technical elements can also be included in the limiting factors.
6. Population density (population/km^2): at higher densities, more residents experience the negative impacts of wind farms, such as noise or visual disturbance.
7. Proximity to populated areas (km): Greater distance from populated areas minimises potential negative impacts and reduces the risk of disapproval from local residents. According to the EIA (Environmental Impact Assessment), the design of wind farms must comply with the minimum spacing between wind turbines and residential areas as defined by legislation and technical standards (for wind turbine heights between 25 m and 50 m, a minimum distance of 1000 m; for heights between 50 m and 100 m, a minimum distance of 1500 m; for heights between 100 m and 150 m, a minimum distance of 2000 m; for heights above 150 m, a minimum distance of 3000 m).
8. Environmental burden: The construction of a wind farm may have an impact on local ecosystems and biodiversity, and may require serious interference with nature, such as the necessary felling of trees.
9. Proximity to the transmission grid (km): Shorter distance to the existing transmission system reduces connection costs and minimises electricity transmission losses.
10. Energy potential of an area (MWh): the estimated amount of electricity that can be generated at a given location affects the overall efficiency and return on investment.

11. Construction costs (EUR million/MW): Includes capital expenditure for the installation of the wind park, with lower costs contributing to faster payback.
12. Noise pollution (dB): the level of noise generated by turbines can affect the quality of life in nearby communities.
13. Other indicators: cost of land, cost of labour, visual impact, soil erosion, labour availability, impact on bird migration routes, seismic activity, runoff, safety requirements, flood threat, and others.

3.3 Multi-Criteria Decision Making (PROMETHEE II)

It is evident that when assessing alternatives for the location of wind farms, a greater number of criteria must be taken into account. Therefore, multi-criteria decision-making methods or multi-criteria evaluation of variants (alternatives) appear to be a suitable tool for deciding on their location. Multi-Criteria Decision Making (MCDM) is a field of decision theory that deals with the selection of an alternative from a set of alternatives according to a number of often conflicting criteria. Currently, a large number of methods have been developed for solving alternative evaluation problems (e.g., Decision Matrix Method - DMM, Forced Decision Matrix Method - FDMM, Analytic Hierarchy Process - AHP, Weighted Sum Approach - WSA, Elimination and Choice Translating algorithm - ELECTRE, Technique for Order of Preference by Similarity to Ideal Solution - TOPSIS, Preference Ranking Organisation Method for Enrichment Evaluations - PROMETHEE, etc.), which are covered in a number of publications, with a relatively comprehensive overview provided by [10-14].

The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) class of methods also belongs to that area of decision theory. PROMETHEE class methods are by their nature based on pairwise comparison of variants. From this class, PROMETHEE I and PROMETHEE II are among the most widely used methods (e.g., [29, 30]), but other modifications have also been developed, such as PROMETHEE V and PROMETHEE VI. Further analyses will use the PROMETHEE II method, which allows for a comprehensive evaluation and comparison of alternatives based on different criteria. The PROMETHEE II method was developed by Brans and Vincke [29] in the 1980s and has since established itself as one of the most widely used methods in the field of decision analysis.

The conceptual strength of these methods lies in their ease of interpretation and flexibility in taking into account both quantitative and qualitative factors. These characteristics are the main reasons for their wide application in areas such as environmental management, real estate assessment and contractor selection. Behzadian, et al. [20] highlight the ability of the PROMETHEE family of methods to adapt to decision situations in which uncertainty plays an important role. They also describe their extension with preference functions based on fuzzy logic, which allow efficient evaluation of alternatives under conditions of imprecision and complexity. In more recent applications, as reported by Sarwar, et al. [31], PROMETHEE methods confirm their ability to generate Pareto-efficient and intuitively ranked alternatives, which represents a significant advantage over other approaches such as AHP or TOPSIS that are based on more rigid forms of aggregation. All these attributes have consolidated the position of PROMETHEE as an integral part of modern decision making.

The PROMETHEE II method aims to produce a complete ranking of alternatives based on the decision maker's preferences. Its main steps include:
1. Normalisation of the decision matrix.
2. Calculation of preference functions.
3. Aggregation of preferences.
4. Calculation of input flows, output flows and net flows.
5. Determination of the final ranking.

This approach allows decision makers to take into account different criteria and preferences when evaluating alternatives.

The PROMETHEE II method is applied in the evaluation of the optimal location of wind parks in the Slovak Republic because it is relatively easy to implement and offers a simple evaluation process. Its shortcomings are negligible and can be overcome by using hybrid and integrated models [19].

The application of the PROMETHEE II method is based on the assumption that there is a set of n alternatives $A = \{a_1, a_2, \ldots, a_n\}$ and a set of k criteria $Y = (y_1, y_2, \ldots, y_k)$, where each criterion $y_{(i)}$ ($i = 1, 2, ..., k$) is assigned a weight $w_{(i)}$ ($i = 1, 2, ..., k$). Let the matrix $\mathbf{V}$ (nxk) represent the values of the n alternatives for the k criteria. For each criterion y_i, ($i = 1, 2, ..., k$), a preference function $F_{(i)}(a_j, a_l) \rightarrow \langle 0,1 \rangle$ is defined that expresses the strength of preference of alternative a_j over a_l in terms of *the i-th* criterion.

The assumption is that each preference function of the corresponding criterion F_i, $i = 1, 2, ..., k$, is a non-decreasing function of the value of the difference of the corresponding criterion values $d_i = v_{ji} - v_{li}$, $i = 1, 2, ..., k$. In general, the preference function F_i and its waveform are shown in Figure 8.
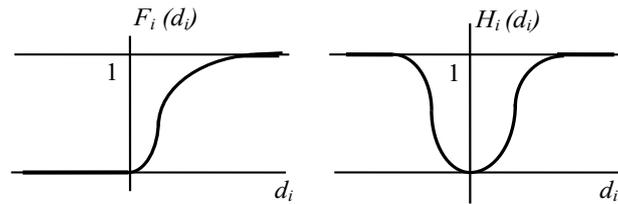
Figure 8 Function flow$F_i(d_i)$ and $H_i(d_i)$

For each $i = 1, 2, ..., k$, the function$H_i(d_i)$ is computed as (1)

$$H_i(d_i) = \begin{cases} F_i(a_j,\ a_l), & d_i \geq 0 \\ F_i(a_l,\ a_j), & d_i \leq 0 \end{cases} \tag{1}$$

a expresses the preferences of alternative a_j, $j = 1, 2, ..., n$, with respect to alternative a_l, $l = 1, 2, ..., n$, and the preferences of alternative a_l with respect to alternative a_j, as well as the indifferences of the two alternatives. The ordered pair $\{y_i, H_i(d_i)\}, i = 1, 2, \ldots, k$, is called the *generalised criterion* (Figure 1). The type of generalized criterion applied is shown in Table 1. The parameter standard deviation of the normal distributionσ is defined for that type of criterion.

Table 1 Type of generalized criteria applied

Type	Definition	The course of the function
VI.	$H_i(d_i) = 1 - e^{-\frac{d_i^2}{2\sigma^2}}$	
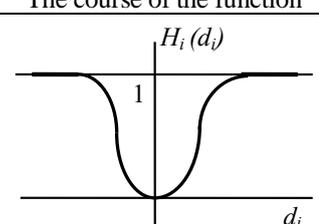
For each pair of variants a_j, a_l, a multi-criteria preference index $\pi(a_j, a_l)$ is defined, which is a weighted average of the k values of the preference functions considered. This index expresses the intensity of the decision maker's preference for the variant a_j, $j = 1, 2, \ldots, n$, with respect to the variant a_l, $l = 1, 2, \ldots, n$, considering all criteria (2):

$$\pi(a_j, a_l) = \frac{\sum_{i=1}^{k} w_i F_i(a_j, a_l)}{\sum_{i=1}^{k} w_i} \qquad w_i \geq 0, i = 1, 2, \ldots, k \tag{2}$$

For the comprehensive evaluation of alternatives using the PROMETHEE II method, the so-called net flow is used, which is calculated from the input and output flows. The output flow values the intensity of preference of the alternative $a_j \in A$ with respect to all other alternatives compared. Conversely, the input flow values the preference intensity of all other alternatives relative to the alternative a_j, $j = 1, 2, \ldots, n$

Output flow (positive outranking flow) for the alternative (3): a_j, $j = 1, 2, \ldots, n$

$$\Phi^+(a_j) = \frac{1}{n-1}\sum_{l=1}^{n} \pi(a_j, a_l) \tag{3}$$

Input flow (negative outranking flow) for the alternative (4): a_j, $j = 1, 2, \ldots, n$

$$\Phi^-(a_j) = \frac{1}{n-1}\sum_{l=1}^{n} \pi(a_l, a_j) \tag{4}$$

Net flow for the alternative (5): a_j, $j = 1, 2, \ldots, n$

$$\Phi(a_j) = \Phi^+(a_j) - \Phi^-(a_j) \tag{5}$$

The PROMETHEE II method results in an overall ranking of alternatives based on net flow. The alternatives are ranked in descending order according to the calculated values $\Phi(a_j)$. A higher value indicates a better alternative in terms of preferences.

4   Optimisation of wind park locations in Slovakia based on PROMETHEE II

Based on the elimination of unsuitable areas for the location of wind farms (geographical and wind requirements), areas with the greatest potential for their construction were identified. The Python programming language and the QGIS geographic information system were used for the analysis as a multi-platform open-source geographic information system that allows viewing, creating, editing and analysing spatial data and producing map outputs [32]. The criteria listed in Table 2 were considered in identifying potential wind farm development sites.

A questionnaire-based communication with selected respondents was used to select the criteria. The results of the communication were reflected in the final set of criteria. The main task of the respondents was to identify those criteria that they considered important in the decision-making process for wind farm siting. The criteria identified primarily included average wind speed (100% of respondents), wind variability (92.9%), impact on birds and bats 92.9%, elevation and terrain profile 64.3%. Other criteria, such as land cost, risk of extreme precipitation, earthquake risk, noise pollution, and total MW power were no longer assessed as particularly important, although they could be used in further analyses.

Thus, the conditions of the criteria for determining the suitability of sites for the construction of wind farms were then formulated in Table 2, taking into account the implemented elimination of unsuitable areas, based on the implemented questionnaire method.

Table 2 Criteria conditions for determining the suitability of sites for wind farms Source: own elaboration

Criterion	Most suitable (1)	Suitable (2)	Average (3)	Less suitable (4)	Least appropriate (5)
Wind speed	>6	6-5	5-4	4-3	<3
Wind energy density	>300	300-250	250-150	150-100	<100
Altitude	<500	500-1000	1000-1500	1500-200	>2000
Slope	<5	5-10	10-20	20-30	>30
Distance from NP, MPA and Natura2000	>5000	5000-4000	4000-3000	3000-2500	<2500
Distance from bird territories	>5000	5000-4000	4000-3000	3000-2500	<2500
Distance from surface waters	>3000	3000-2000	2000-1000	1000-500	<500
Distance from the airport zone	>10000	10000-8000	8000-7000	7000-5000	<5000
Distance from power lines	<2000	2000-3000	3000-4000	4000-5000	>5000
Population density	<10	10-50	50-90	90-110	>110
Distance from residential zone	>1500	1500-1000	1000-700	700-500	<500

Based on the above, suitable locations for wind farms have been generated and are represented by the suitability map in Figure 9. Suitable areas are highlighted in blue and identify areas that are mainly located in the lowlands with stable wind conditions.

From the suitable areas, the territories of the municipalities Tešedíkovo, Radošovce, Komárovce, Svodín, Vrakúň and Černochov (marked in red in Figure 9) were identified as the most suitable based on the established criteria and further analysed using the PROMETHEE II method.

Only some of the criteria that were used to plot the suitability map were applied in the PROMETHEE II analysis, namely: wind speed, wind energy density, elevation, slope and population density. Table 3 presents the values of each criterion considered for each identified area (*L1, L2, ..., L6*) and the weights assigned to each criterion regarding its importance (*k1, k2, ..., k5*). The weights were determined based on a questionnaire completed by experts on the subject. As already mentioned in section four, the analysis was carried out in the selection of the preference function (Table 1), due to the impossibility of quantifying the indifference and preference thresholds based on the qualitative data obtained from the questionnaires. The required parameters (standard deviation) for the above preference function were obtained based on the values presented in Table 3.

The wind speed and wind energy density criteria were maximised, while the others were minimised.

Based on the values shown in Table 3, the values of the preference functions can be calculated for each criterion *k1* to *k5*, each site *L1* to *L6* and compared against all other sites. In this way, 6 different tables with preference values for each criterion were created. Then a weighted sum was made from the calculated values using defined weights (multi-criteria preference index - key 4 values in rows and columns in *L1* to *L6*).
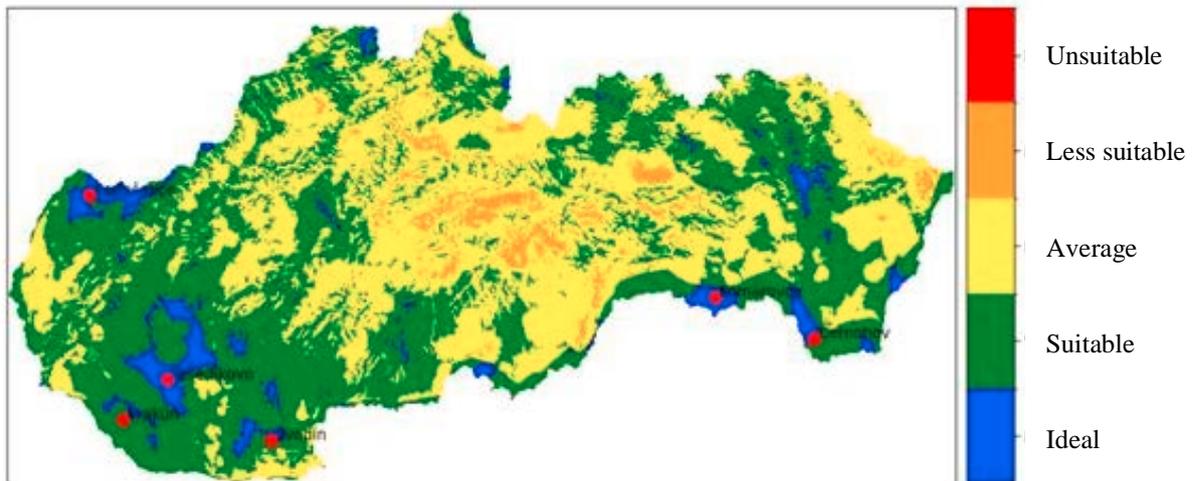
Figure 9 Map of the suitability of wind farm locations, source: own elaboration based on [26]

Table 3 Values of criteria in the calculation of PROMETHEE II Source: own elaboration

Criterion		*Max/Min*	*L1* Tešedíkovo	*L2* Radošovce	*L3* Komárovce	*L4* Svodín	*L5* Vrakúň	*L6* Černochov	Parameters Weights	σ
Wind speed	k1	*Max*	6.38	6.77	4.76	6.15	6.56	5.29	0.25	0.72
Wind energy density	k2	*Max*	302.51	375.94	207.51	268.39	324.92	219.97	0.35	58.68
Altitude	k3	*Min*	112.98	189.58	213.80	193.74	112.70	102.23	0.1	45.62
Slope	k4	*Min*	6.46°	9.5°	12.06°	11.00°	6.42°	5.83°	0.05	2.43
Population density	k5	*Min*	163	68	48	44	75	39	0.25	42.33

Table 4 presents the aggregated values of the preference functions from which the corresponding output and input flows can be calculated (Table 4). The output (positive) flow Φ^+ expresses how strong the preference of one location is relative to the others. The input (negative) flow Φ^-, on the other hand, values the strength of the preference of all other locations with respect to a given location. For the PROMETHEE II method, however, the net flow Φ (Table 4) can be calculated as the difference of the output and input flows.

Table 4 Preference function values and calculation of flows, source: own elaboration

	L1	*L2*	*L3*	*L4*	*L5*	*L6*	Φ^+	Φ
L1	0	0.0244	0.0680	0.0680	0	0.0436	0.2040	-0.1811
L2	0.0934	0	0.0680	0.0680	0.0934	0.0436	0.3664	0.1437
L3	0.0498	0.0498	0	0	0.0498	0	0.1494	-0.2902
L4	0.0498	0.0498	0.1178	0	0.0498	0.0436	0.3108	0.0325
L5	0.1178	0.0244	0.0680	0.0680	0	0.0436	0.3218	0.0545
L6	0.0743	0.0743	0.1178	0.0743	0.0743	0	0.4150	**0.2406**
Φ^-	0.3851	0.2227	0.4396	0.2783	0.2673	0.1744		

The calculated net flow values Φ allow the alternatives to be ranked from most preferred to least preferred site. Since the higher the net flow value Φ, the better the alternative, the highest net flow value Φ is 0.2406 for site *L6* indicating that in terms of the defined criteria the best location for the wind park can be considered to be the area of the municipality of Černochov. The ranking of the analysed areas *L1, L2, ..., L6* is given in Table 5.

Table 5 Resulting ordering of alternatives using the PROMETHEE II method, source: own elaboration

Order	Φ	Location	Village
1.	0.2406	*L6*	Černochov
2.	0.1437	*L2*	Radošovce
3.	0.0545	*L5*	Vrakúň
4.	0.0325	*L4*	Svodín
5.	-0.1811	*L1*	Tešedíkovo
6.	-0.2902	*L3*	Komárovce

5   Discussion

Recently, the use of renewable energy sources has become an important issue in the context of global warming and the resulting concept of sustainability (sustainable development aims to meet the needs of the present generation without compromising the ability of future generations to meet their own needs, and must reconcile the three key elements of economic growth, social inclusion and environmental protection). In the field of renewable energies, wind energy is one of the promising solutions to reduce dependence on fossil fuels and improve the environmental balance of countries. However, its use in the Slovak Republic is still very limited compared to other European countries.According to the data of the Office for Regulation of Network Industries, wind energy in 2016 produced an annual amount of generated electricity of only about 6 MWh, while neighbouring countries had wind sources with a total installed capacity of: the Czech Republic - 217 MWh, Poland 1 616 MWh, Austria - 1 084 MWh, Hungary - 329 MWh and Germany 29. These figures also indicate a great potential for further development, as according to various estimates, up to approximately 20% of the territory of Slovakia is suitable for the construction of wind power plants (https://www.iusaegis.sk/uncategorized/veterne-elektrarne-v-podmienkach-slovenskej-republiky/).

This is why the issue of the location of wind farms in Slovakia is currently a very topical problem in the context of sustainable development policy. Still, this issue represents a very complex system of decision-making, which requires detailed analysis in many areas. A large number of geological and socio-legal factors have to be considered in the construction of a wind park, which may include suitable climatic conditions, terrain profile, availability of infrastructure, as well as the impact on the local population and various economic and environmental factors. In the Slovak Republic, these conditions are defined in the Directive of the Ministry of the Environment of the Slovak Republic of 21 April 2010 No 3/2010 'Standards and limits for the siting of wind power plants and wind parks in the Slovak Republic' and in Act 309/2009 Coll. on the promotion of renewable energy sources and high-efficiency combined production In 2019, the Government of the Slovak Republic approved the National Energy and Climate Plan (NECP) until 2030, which aims to achieve a level of installed capacity of wind power plants of 500 MWh by 2030 in the field of wind energy use in Slovakia (in 2020 it was only 4 MWh).

When determining the suitable location of the wind park, it is necessary to examine primarily suitable geological conditions for its construction, but this group can also include the availability of the site for construction machinery, the distance of high and low voltage power lines from the planned location. The overall safety of operation, including sufficient distance from populated areas, must be emphasised in the impact of its construction. Furthermore, economic criteria are also important, e.g. the cost of construction, including the cost of land, the cost of transporting materials, etc., but also the cost of operation, which is again the cost of transport, or the average wages in the area. In addition to the above criteria, a prerequisite for the selection of a site for the construction of a wind park is the preparation of an Environmental Impact Assessment (EIA) study, the cost of which is relatively high and affects the overall investment intensity of the construction of the wind park under consideration.

In the presented analysis, the criteria used were those that were considered important for the selection of the optimal location for wind parks in Slovakia based on the survey. Based on the criteria considered, a map of the suitability of wind park locations was generated, which divided the territory of Slovakia into areas that are not suitable for construction at all (e.g. for nature protection reasons) to the most suitable areas. From these areas, 6 areas were identified, which formed the basis for their comparison with each other by means of the chosen PROMETHEE II method.

As a result of the solution, the wind park locations in each area are ranked based on the calculated values of net flows in Table 6. The calculated ranking for the six identified areas is Černochov, Radošovce, Vrakúň, Svodín, Tešedíkovo, Komárovce, with net flux values of 0.2406, 0.1437, 0.0545, 0.0325, -0.1811, -0.2902, while allowing to interpret the preferences of the individual territories. Based on the performed calculations, it is possible to prefer the territory of the village Černochov, which is located in the south-east of Slovakia in the Košice region, among the identified areas.

Based on the research conducted, the implemented procedure can be summarised in the following steps:
1. Elimination areas
    1.1. Geographical location requirements
        1.1.1. Areas suitable for construction
        1.1.2. Areas conditionally suitable for construction
        1.1.3. Areas unsuitable for construction
    1.2. Wind location requirements
        1.2.1. Wind speed
        1.2.2. Average wind energy density
2. Formulation of criteria for determining the suitability of sites
    2.1. Wind speed
    2.2. Average wind energy density
    2.3. Landform
    2.4. Distance from protected areas
    2.5. Distance of other limiting elements

    2.6. Population density
    2.7. Proximity to populated areas
    2.8. Environmental burden
    2.9. Proximity to the transmission network
    2.10. Energy potential of the area
    2.11. Construction costs
    2.12. Noise pollution
    2.13. Other indicators
3. Choice of multi-criteria variant evaluation method (DMM, FDMM, AHP, WSA, ELECTRE, TOPSIS, PROMETHEE, etc.)
4. Calculation of the best location of wind farms based on the selected method of multi-criteria evaluation of variants

This generalised procedure can serve as a useful tool for solving wind farm siting decision-making problems. However, when the requirements are modified based on legislative regulations (elimination of areas) and specified criteria are applied (determination of site suitability), it can also serve as a general guide for siting any facility.

6 Conclusion

The transition to renewable energy is a vital component of sustainable development, and wind energy plays a central role in reducing reliance on fossil fuels. However, Slovakia's utilisation of this resource remains far below that of neighbouring EU countries. This study addressed the challenge of siting wind parks by combining spatial analysis with multi-criteria decision-making using the PROMETHEE II method.

Through a structured elimination of unsuitable areas and a GIS-supported identification of technically feasible zones, six candidate sites were selected and evaluated. The PROMETHEE II method provided a transparent and quantitative framework for ranking these sites based on expert-weighted criteria, including wind speed, wind energy density, elevation, slope, and population density. Among them, Černochov emerged as the most suitable location.

The methodology developed in this study can serve as a generalised decision-support tool for policymakers and investors. Moreover, it demonstrates that, despite regulatory and spatial limitations, Slovakia has viable opportunities to expand wind energy infrastructure, thereby contributing to national and EU climate goals.

Future research should focus on extending the analysis with more detailed datasets, incorporating dynamic environmental assessments, and exploring alternative MCDM approaches to validate or compare results. Doing so will enhance the robustness and applicability of the framework for future renewable energy investments.

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Changes in resilience models in the healthcare supply chain

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Keywords: healthcare, supply chain, resilience, supply chain management.
Abstract: The events of the last five years have had a huge effect on the healthcare supply chain. The system has encountered challenges such as the COVID-19 pandemic and political conflicts. At the same time, sustainability pressures are increasing. These disruptive incidents have revealed weaknesses in the supply chain and lack of resilience. As a result, changes in resilience models have begun to be planned and implemented. The article looks at the main changes in resilience models, emphasizing new models, measures, and attitudes to ensure healthcare logistic. Factors such as risk forecasting, diversification of supply sources, the impact of digitalization, timely inventory management, and strengthening cooperation with suppliers are analyzed. Models that are oriented toward greater flexibility and systemic resilience assessment in general are also discussed. Based on the literature review, it can be concluded that the development of dynamic, predictive, and technology-based robustness models can minimize the harm caused by supply chain disruptions and ensure the stability of the healthcare system. The results of the review indicated that the newest direction for models is the flow of smart technologies. This is expensive, but digitalization can ensure a robust supply chain in the healthcare sector.

1   Introduction

The pandemic has shown that the healthcare supply chain is extremely sensitive and vulnerable. Ongoing political conflicts and the growing importance of sustainability have prompted both scientists and practitioners to look for new ways to ensure the resilience of the system. The OECD report (2025) notes that the dependence on smaller supply sources is increasing. As a result, the vulnerability of the supply chain is growing. The healthcare sector needs to be resilient to unpredictable disruptions, as the services it provides are directly related to saving lives and safeguarding health. Supply chains are complex, interconnected, and limited, which has led to a major shift in how we think about resilience. New models that are more adaptable, more accurate in their predictions, and more technologically innovative need to be planned and developed.

For a long time, logistic models were based on the just-in-time principle, with centralized suppliers and minimal stocks. However, over time, these methods proved to be outdated and unable to protect against sudden disruptions. During COVID-19 in particular, there was a shortage of equipment and medicines, and supply processes were delayed. As a result, it became clear that traditional supply models are more suitable for responding after an event has occurred. Flexible and proactive supply chain resilience models need to be developed to prevent unpredictable events. It should be noted that the development of resilience strategies is integral to effective risk management in the supply chain. In view of this, it is clear that resilience should become a priority for the management of organizations. According to the latest provisions of the World Economic Forum (2025), it is necessary to strengthen not only the operations of the chain, but also to increase the resilience of the employees themselves.

It should be noted that resilience is now understood not only as the capacity to recover from disruptions, but as the ability of the entire system to predict, adapt, and maintain its effectiveness even when circumstances change.

This article aims to look at changes in vulnerability models for the healthcare supply chain. It also assesses the reasons for these changes and analyzes current solutions and challenges faced in this sector. Furthermore, it also looks at how these trends can help make the system more robust and sustainable. Based on a review of the scientific literature, it is discusses trends in vulnerability models in the healthcare sector. The relevance of the analysis is determined by the need to develop more efficient, sustainable, and resilient supply chains that would ensure the stability of the healthcare system and its ability to respond to emerging critical situations.

The following tasks were outlined to achieve the purpose of the study:
O1.: to conduct a comprehensive analysis of the literature;
O2.: to provide detailed changes in resilience models and their impact on supply chain operations.

Statistical methods were used to analyze the data and draw conclusions. Tables and diagrams detail the results, with the methodology of the literature analysis presented in the chart.

The article consists of the following parts: introduction, literature review, research methodology, presentation of results, and discussion. The introduction briefly summarizes the relevance of the problem. It explains the reasons for the vulnerability of the healthcare supply chain and what is needed to make the system resilient and ensure service delivery. The literature review section presents basic definitions, research made by other scientists, and their results. The methodology part details the steps and actions taken to perform the literature review. The results obtained from the analysis are presented in the following section. The results are described and illustrated graphically. The discussion section summarizes the results, the findings of other researchers' analyses, and outlines directions for future research.

2   Literature review

This subsection provides definitions of key terms that are important and used throughout this article.

Supply chain – a network of interrelated organizations and service providers that work together to ensure the quality of products or services and protect information, equipment and facilities at every stage of the supply chain [1]. This is a huge flow of information, finances, and management.

Healthcare supply chain - is a flow of management stakeholders, manufacturers, distributors, hospitals, pharmacies, insurance providers, and, of course, patients and the flow of all resources from the manufacturer to the patient [2]. The healthcare supply chain consists of the supply of medicines, medical equipment, various devices, and other essential resources. The healthcare supply chain is particularly vulnerable to disruptions, as the health of the entire population, and often people's lives, depend on its proper functioning. In the last few years, the supply chain has been affected by factors such as the pandemic, political conflicts, climate change challenges, and cyber security. These major events have highlighted the weak parts of the supply chain. This has led to improvements in existing models and the search for new models to make the supply chain more resilient.

Supply chain resilience - this is the ability of the supply chain to adapt to unexpected disruptions, prevent the spread of disruptions by maintaining control over structures and functions, and recover, ensuring the continuity of the supply chain [3]. Resilience is a property that is necessary for both organizations and processes.

Businesses only recognized the importance of resilience around 2000, when tragic events shocked the world. Fuel protests in Europe and a terrorist attack in the USA 2001 [1]. These events prompted concern to find new ways to prevent such disasters in the future. Resilience is the fundamental ability of a supply chain to cope with and adapt to unanticipated disruptions as they occur [2]. However, it can have more meanings depending on the perspective [3]. Since the start of the pandemic, this capability has become a priority for many organizations   [4-6].

Several common concepts of supply chain resilience can be found in the scientific literature it is show in Figure 1.
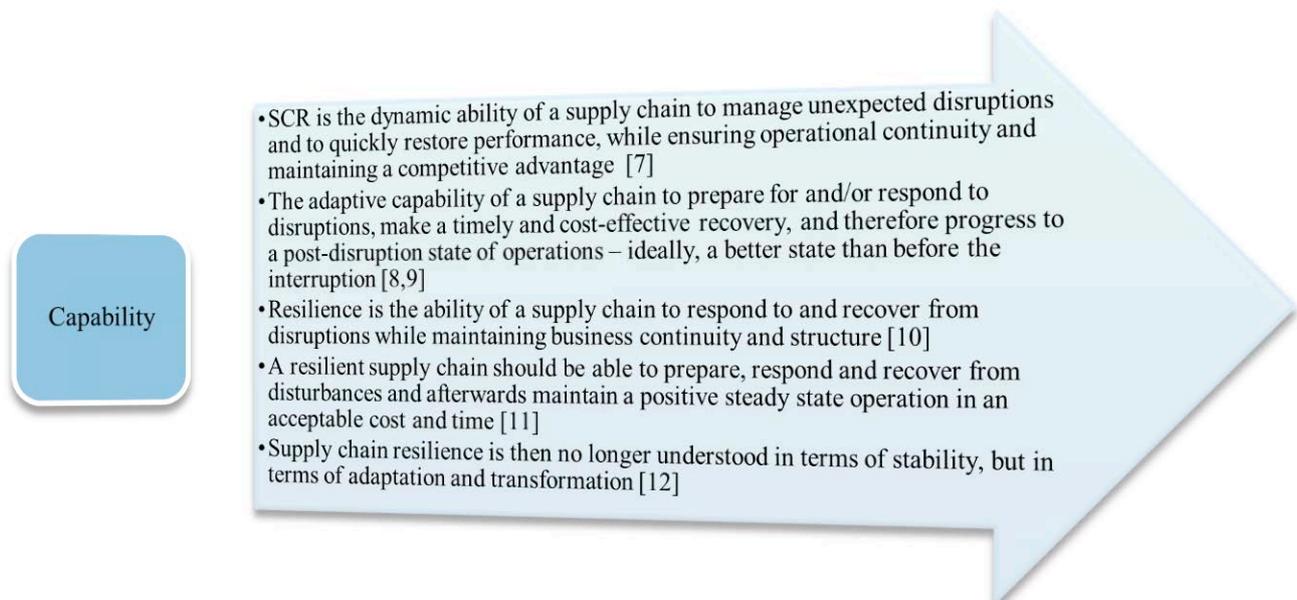
Figure 1 Definitions of supply chain resilience [7-12]

To summarise the Figure 1, supply chain resilience is a capability. Most authors also agree that the ability of the supply chain to withstand unforeseen events and to return to its original state are the most critical resilience factors.

Supply chains in the healthcare sector are different because the focus is on saving lives rather than generating income. In this way, the health system supply chain is unusual [13]. In the supply chain, healthcare providers (clinics, hospitals, private/public) are the organizations that work with patients and create demand throughout the healthcare supply chain [14]. They differ from typical supply chains in terms of high-value products and high complexity and unpredictable provision. There are shown the supply chain resilience models analyzed by the authors in the Figure 2.

Figure 2 The most common supply chain resilience models

Several insights can be made when evaluating the Figure 2. There are many models of resilience in the entire health system - diagnostic questions are analysed, the resilience of health system workers is extensively explored, especially during the Covid period. There is not much research that examines supply chain resilience patterns across the entire healthcare system. We can see that in previous years models are analyzed which explore the factors of cooperation, organizational cultural influence. In recent years, we can see a trend towards the increasing use of models based on smart technologies. They are fast, reliable, able to process huge amounts of information [15]. Artificial intelligence-driven techniques, such as forecasting systems and identification of supplier-buyer relationships, can be valuable in increasing supply chain visibility [16]. Supply chain visibility can be provided as an integrated application solution.

According to Pournader (2020), health system supply chains in particular should adopt a multi-level approach to addressing resilience management. This approach includes the management between the individual, the organization, and all stakeholders and their combined impact on supply chain resilience [17]. However, models are affected by many drivers.

2.1   Determinants of changes in patterns

Both societal and global political developments have created the conditions for the health system to change and adapt. A healthcare system that wants to ensure proper functioning must take group measures. Resilience solutions must integrate technology, collaboration, and system visibility [18]. It should be noted that research is increasingly recognizing the usefulness of innovative technologies in increasing the resilience of the supply chain and improving its visibility. However, there are still not enough analyses to confirm this [19]. Based on scientific literature, below are several factors that are significant for the creation of new supply chain resilience models.

Supply chain risk management
In addition, supply chain resilience is closely related to supply chain risk management. After all, the most important goal of risk management is to protect the supply chain from unwanted events [6]. According to Majumdar (2021), organizations that want to create a resilient supply chain should prioritize risk mitigation strategies, and based on the results, adopt a set of strategies [20]. Choosing the right strategies can make sure the chain keeps running smoothly.

Innovative technologies

Another significant reason is technological changes. According to Arji (2023), artificial intelligence, blockchain, big data analytics, and modelling are the most important technologies used in healthcare supply chain management [18]. In the literature, digital technologies are considered essential resources for supply chains to stay up and running. Using these technologies makes supply chains more resilient, agile, and visible [19]. Digitalization is considered an important element in a huge variety of logistics elements.

Global disruptions

The COVID-19 pandemic is also a significant factor that has created a need to improve existing resilience systems. Indeed, the disruptions caused by the pandemic have highlighted serious weaknesses in the health system. During the pandemic, it was difficult to ensure the delivery of health services. This has led to an increased need to strengthen the resilience of the whole health care system [20,21].

Sustainability factor

Sustainability and resilience. The growing importance of sustainability highlights that harmonizing environmental and governance aspects positively impacts supply chain efficiency [20]. Based on the latest academic insights, sustainability is currently one of the most crucial aspects of healthcare systems and one of the most pursued practices [21]. The healthcare sector comprises a significant part of the economies of both the world and every country. Therefore, it must follow sustainability trends [22].

Legal provisions

In addition, changes in political decisions and regulatory frameworks must be mentioned. Based on the World Health Organization's position, countries are increasingly required to ensure the preparedness, resilience, and sustainability of their supply chains [23]. Mandal (2023) published a study in 2017 that was the first to mention indicators for measuring resilience in the healthcare industry.

2.2 Overview of current models of resilience

The issue of supply chain resilience has been under discussion for some time. Some countries have tried to develop possible resilience models. In this paragraph, it will be discussed how they have fared and succeeded.

Figure 3 shows the most prominent trends in resilient models.

Based on a review of the literature and the work of other authors, resilience models can be divided into the following groups:

- Technological;
- Organizational;
- Sustainability;
- Human flows.

Technological models are the fastest growing area, but their implementation requires the largest investments and poses new risks. Organizational models are more dependent on the quality of cooperation, but can be implemented more quickly and cheaply. Sustainability models provide a long-term competitive advantage but may conflict with short-term economic goals. Human resource resilience is a key element in ensuring that technologies and processes are effectively adapted in crises. Future research should combine all four categories to achieve systemic resilience in the healthcare delivery chain.

Trends of resilience models:

• Developing the use of innovative technologies: digital technologies such as artificial intelligence and big data mining have been introduced in many countries around the world. Due to innovation, organizations have been able to quickly optimize stock management and forecast demand.

• Blockchain technology: blockchain technology is being widely deployed to ensure supply chain transparency and security.

• Supplier diversification: one of the tools to reduce supply chain risks. It is the possibility of having all suppliers in one place, as well as having several suppliers for the same product. This ensures that the supply chain can respond quickly if any source of supply becomes inoperative.

• Integrating multiple systems: integrating the health system supply chain and crisis management in general into one single system. This creates a common strategy to ensure supply, storage of products, and response to a crisis incident.
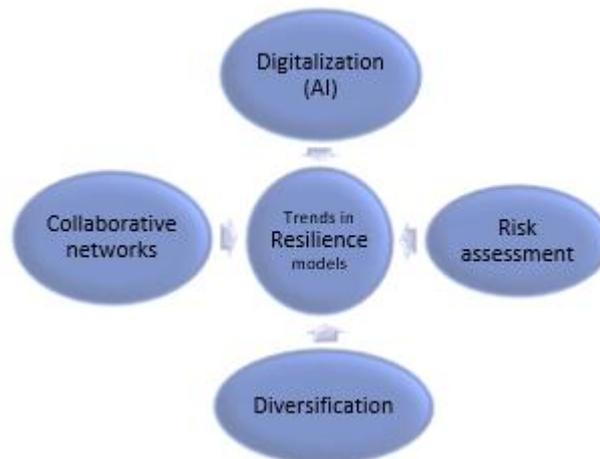
Figure 3 Trends of resilience models

2.3 Challenges of new models implementation

So, the studies show how important it is to use smart technology and develop new models to keep supply chains working smoothly. But there are some challenges to implementing this.

First of all, it should be noted that research on barriers to technology implementation is limited. The studies that have been conducted are fragmented. However, one of the key problems identified is miscommunication between managers and implementers. Other barriers include inter-organizational, social, and environmental issues [24].

Furthermore, scientists no longer doubt the importance of digital technologies in ensuring the resilience of organizations. However, at the same time, new technologies increase cyber security risks for organizations implementing this process [25]. The risk of data leaks and cyber attacks is growing.

In addition, every organization faces significant organizational challenges when introducing improvements. Due to changes in the organizational and hierarchical structures, collaboration between departments is becoming complicated. This hinders the dissemination and implementation of new technological solutions [26]. It has also been found that a lack of understanding among senior staff and management poses major challenges to the adoption of innovations [27]. It should be emphasized that the success of any technically innovative solution depends on the competence and skills of qualified professionals. However, considering that the healthcare sector is not attractive to these professionals, organizations may face challenges related to the lack of technical competence [28]. Therefore, it is the healthcare sector that must make efforts to ensure that the necessary functions are performed by competent personnel.

Also, successful technological growth needs enough management of financial resources [29]. In order for new systems to function effectively and remain competitive, they need to be maintained and continuously improved. This requires ongoing financial resources [30].

3   Methodology

This review aimed to analyze which supply chain resilience models are applied in the healthcare system and how they have changed. To this end, a literature review was conducted to identify trends in the relevance of the topic, changes in models, and their causes. Future research directions were also determined.

Criteria for inclusion of literature sources:
- Scientific articles in peer-reviewed journals;
- Publications from 2014 to 2024;
- Articles in English;
- Research investigating models of resilience in healthcare supply chains.

Criteria for exclusion of literature sources:
- Articles in non-peer-reviewed journals;
- Research papers not related to supply chains in the healthcare sector.

The search for publications was conducted in the following databases: Scopus, Web of Science, PubMed.
The following code phrases were used for the search: "healthcare supply chain" AND "resilience models".

In addition, a time filter (articles published between 2014 and 2024) and a language filter (only articles in English) were used to select the articles. When processing the list of articles, the data was transferred to Excel. The publication selection procedure is illustrated in the Figure 4 below.

After selecting the appropriate articles, a further selection was made based on the keyword "resilience models." This was done with the aim of identifying traditional and new resilience models and assessing their suitability for the healthcare system in emergency situations. The application of models is analyzed and conclusions are drawn from selected publications.

When evaluating the results, we would like to draw attention to the year 2020. Scientists regard 2020 as the turning point when the topic of resilience became particularly relevant.

Figure 4 Publication selection process

4 Results and discussion

A review of the literature uncovered a few trends in models of resilience in healthcare supply chains. First, models have become systemic, involving both technological and organizational decisions. Second, resilience is equated with the ability to predict and adapt, rather than just react after an event. There is also a clear role for technology in creating a smooth supply chain. Furthermore, a method of supplier diversification has been discovered that reduces territorial dependence. In addition, the importance of collaboration should be highlighted. All this shows that achieving resilience is becoming a strategic priority for organizations.

Table 1 below shows the number of publications found in databases during the period under review.

Table 1 Number of articles by topic

Year	Databases		
	Web of Science	Scopus	PubMed
2014	0	0	0
2015	0	0	0
2016	0	0	0
2017	1	1	0
2018	1	0	0
2019	2	2	1
2020	4	4	4
2021	13	5	4
2022	14	8	7
2023	15	15	6
2024	15	31	7
Total:	**65**	**66**	**29**

The results of Table 1 reveal that the top of the issue's relevance will be in 2022-2023. This is the period following the COVID-19 pandemic and the start of military conflicts. These data confirm the results of studies carried out by other researchers. Considering the number of publications in the relevant years, it is worth taking data from 2020 onwards for future research.

Further analysis of the literature resulted in a counted number of articles that examined health system resilience models during the period in a review. The results are presented in Figure 5.

Changes in resilience models in the healthcare supply chain
Alma Cerkauskiene, Ieva Meidute-Kavaliauskiene
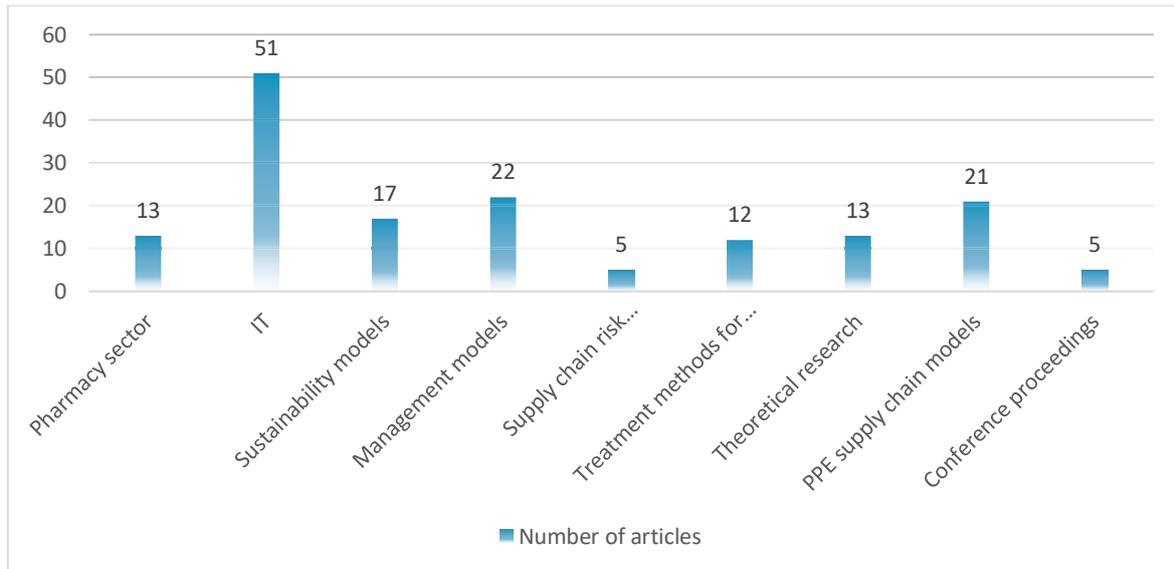
Figure 5 Number of publications of resilience models

The study's results indicate that digitalization, collaboration, and sustainability are the most crucial factors in ensuring supply chain resilience. The findings of the analysis confirm the results of other researchers that organisations are increasingly implementing digital technologies and seeking sustainability.

The data analysis aimed not only to clarify the context in which the models are applied, but also how the scientific community's interest in this issue has changed. Figure 6 shows how researchers' attention to the vulnerability of the healthcare supply chain has changed over time.
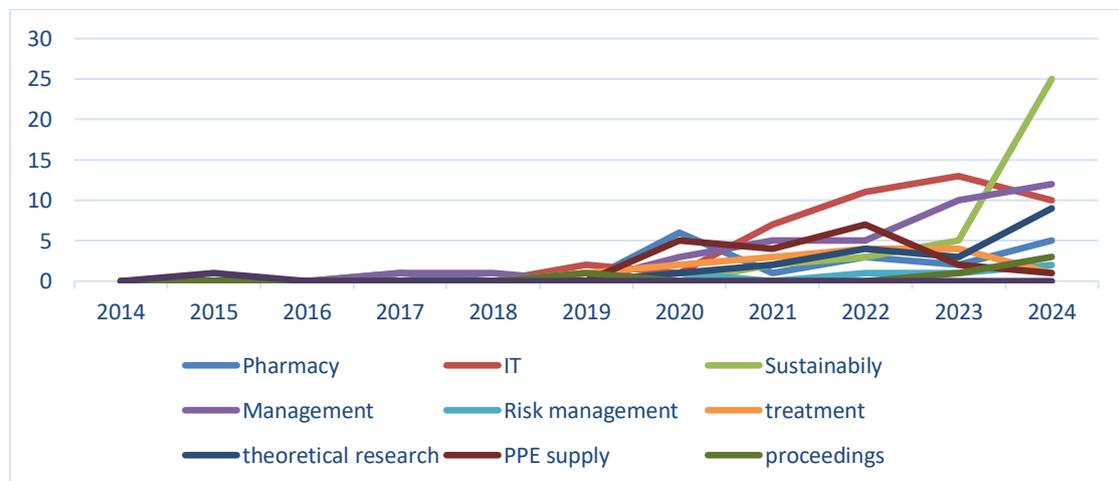
Figure 6 Trends in interest in the resilience of the healthcare supply chain

Figure 6 shows that the relevance of the topic is increasing towards 2019. The importance of IT and digitalization is already becoming significant. The peak for most of the models studied can be considered to be 2022-2023. The relevance of IT and supply chain management models is growing particularly rapidly. It is likely that digitalization will accelerate and the need for sustainability will increase in the future.

Changes in supply chain resilience patterns in the healthcare sector have a major impact.

The analysis indicates that the development of new preparedness strategies requires a new understanding and management of risks in the healthcare supply chain. In order to increase understanding, it is necessary to invest in the human flows. Employees must not only be resilient, but also have the necessary skills.

• The use of digital technologies enables organizations to detect disorders early, evaluate situations flexibly, and make timely decisions. Artificial intelligence devices are equipped to continuously monitor the operating environment and identify disruptions. Technology enables systems to be faster, with the ability to handle large amount of data, so that all processes are faster. This increases the efficiency of health system operations. Integrating social factors into supply chain resilience strategies is a way to lower the risks to the whole system.

• Intersectoral collaboration. Agility in partnerships reduces risks associated with dependence on suppliers and circumstances. Integrating social factors into supply chain resilience strategies is a way to lower the risks to the whole system.

• The role of sustainability is crucial. Sustainable factors are among the most significant risk management factors. Integrating social factors into supply chain resilience strategies is a way to lower the risks to the whole system.

• Financial costs. According to the World Health Organization, not all healthcare systems have the same financial capacity to keep up with technological innovations [31]. Countries should look into strategic investments to build new and promising ways to be more resilient.

In general, the impact of changes in models in healthcare involves both processes and deliverables, the advantages offered by the new models contribute to a more flexible, responsive, and socially responsible healthcare system supply chain. All of this is crucial when it comes to preparing for future crises. The new strategies have clear benefits in terms of enhancing the delivery of healthcare services and increasing the resilience of the whole system. However, the challenges of developing and implementing models highlight the complexity of transitioning to new strategies.

Recent studies examine the potential of artificial intelligence and blockchain technologies in ensuring the resilience of healthcare systems. However, the business community is calling for a return to a focus on people—developing their competencies, skills, and, of course, resilience. And ultimately, we see that we cannot rely only on technology, just as we cannot depend entirely on people. To achieve optimal results, a symbiosis between people and technology is essential.

5   Conclusions

In summarizing, it can be seen that resilience strategies in the healthcare supply chain are strongly dependent on the uncertain global situation. In the future, resilience models should be driven by technological innovations, new methods of collaboration, and sustainability requirements. The modern supply chain must be not only robust, but also agile, sustainable, and socially responsible. Scientists, politicians, and practitioners must cooperate to create resilient supply chains. Today's supply networks are oriented toward smart systems and process automatization. There is a tendency to have more than one supplier and to ensure the sustainability of operations.

Today's supply networks are oriented toward smart systems and process automatization. There is a tendency to have more than one supplier and to ensure the sustainability of operations. The development and implementation of new resilience models unequivocally require significant financial investment and strong political decisions.

Based on the results of the review, there are some recommendations for politicians, leaders, and academics:

• Create and incorporate safety systems to minimize cyber risks and protect data.

• Encourage multisectoral cooperation to provide all organizations with sufficient financial resources.

• Focus not only on technological aspects, but also on human resources to build organizational resilience.

This analysis presents not only the resilience models that are currently in place or being developed in the healthcare supply chain. It also analyzes changes in these models and their causes. In addition, the models are briefly described and their differences are highlighted.

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Data analytics for supply chain resilience: a multiple case study analysis

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Keywords: data analytics, supply chain resilience, data quality, data integration, multiple case study.
Abstract: Developing supply chain (SC) resilience through data analytics has emerged as an important area of research recently. However, the current literature offers a limited common understanding of the impact of data analytics enabling SC resilience across several phases of resilience development. Thus, this study aims to explore the role of data analytics in identifying potential supply chain disruptions, mitigating risks, and improving supply chain performance. We use a multiple-case study qualitative research approach to understand how firms successfully implement data analytics in their supply chain operations. The research data were collected through semi-structured interviews conducted with 7 supply chain experts from six different firms in Finland. The analysis includes investigating specific tools and techniques used, the data sources, and the types of data analyzed. In addition, this study explores the challenges firms face during the implementation of data analytics and how data analytics effectively builds supply chain resilience. The findings highlight that data analytics offers valuable insights into the supply chain and supports firms to proactively identify and mitigate risks. Furthermore, this study highlights the importance of data quality, data integration, and the need for new skills and capabilities in implementing data analytics in the supply chain. This study contributes to the emerging literature on data analytics' role in developing supply chain resilience and offers insights into the challenges and opportunities associated with its practical implementation. This study offers several theoretical and practical implications for supply chain research and managers.

1   Introduction

Supply chain (SC) resilience has emerged as an important point of discussion more than ever since COVID-19 hit as the pandemic's unexpected disruptions resulted in exposing the vulnerabilities of SCs and their effects on supply shortages. Thus, SC resilience is considered a firm's key capability which enables and sustains its competitive advantage in a fast-paced and uncertain business environment. However, effective SC resilience requires access to accurate and up-to-date information on SC operations. This, in turn, is driving companies to rely on data and use it as a tool in developing SC resilience. Data is considered a large and complex set of information generated by organizations. Emerging technologies such as artificial intelligence (AI) and the Internet of Things (IoT) have enabled the data revolution – a powerful tool for firms to access the information needed to enhance their SC operations. Therefore, data analytics can support firms in gathering, processing, and analyzing a large volume of data from different sources, enabling insights into their SC operations, which can help firms recognize any potential risks, offer real-time visibility, forecast demand, optimize inventory levels to enhance SC resilience [1,2]. Moreover, data analytics enables firms to enhance communication and collaboration with suppliers and customers [3]. It helps in predictive analytics, enabling firms not only to anticipate any possible disruptions but also to proactively deal with these potential disruptions [4,5].

The importance of using data analytics in developing SC resilience has been growing because of globalization and the increasing complexity of SCs. As SCs span multiple regions, countries, and continents, firms are required to tackle a variety of risks, including natural calamity, instability in geopolitical situations, and cyber-attacks. To overcome these challenges, data analytics support firms in developing SC operational views that are more comprehensive, enabling the identification of risks and developing mitigation strategies. This helps firms foresee and adjust to any disruptions and operate sustainably even when certain challenges are unforeseen [6]. The topic of SC resilience through data analytics

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has emerged as an important area of exploration in the literature. Several scholars have highlighted the importance of descriptive and predictive analytics within prescriptive models in modern SCM providing important parameters and insights that impact the performance of the models and SC operations [7,8]. However, there remains a limited amount of research investigating the impact of data analytics enabling SC resilience [9] and the progress across various phases of resilience development of SC has been inconsistent [10]. Thus, it is reasonable to argue that prior literature remained fragmented and has failed to explain how data-driven decision-making enhances the entire cycle of SC resilience. In the context of this research, the cycle of SC resilience refers to the stage model: identification and mitigation, response, recovery, and learning and improvement, as defined by [11]. Furthermore, the author highlights that there is a lack of a comprehensive understanding of SC resilience and its implementation strategies.

Therefore, the purpose of this research is to fill these gaps by exploring the impact that data analytics can have on developing SC resilience. This study offers practical knowledge by highlighting some key success factors for organizations that aim to enhance their SC resilience by utilizing data-driven decision-making. This research delves into the discussion of different ways where data can be used to enhance SC resilience – including managing risks, improved visibility, predictive analytics, quick decision-making, and enhanced cooperation between stakeholders. Thus, we ask the following research question, "How can data analytics be implemented for decision-making and optimizing the strategy to build SC resilience?" This research follows a multiple case study qualitative research approach and utilizes semi-structured interviews conducted with seven SC experts from six different firms in Finland. The study provides valuable insights into the emerging literature on data analytics and SC resilience by shedding light on the challenges in ensuring data quality and integration, new skills and capabilities, and opportunities related to the effective implementation of data analytics to enhance SC resilience.

2 Literature review
2.1 SC disruption and resilience

The SC concept has been studied with different angles and contexts for several decades. Since the SC involves networks, facilities, and distribution from upstream suppliers to downstream customers and end consumers, the SC plays an important role in business operations. However, there have been several SC disruptions, as SC needs to deal with several partners, stakeholders, information, and product flow throughout the whole chain. This makes the whole SC a complex process of moving products and information exposing organizations to unforeseen disruptions [12], thus affecting the operational performance of businesses through delays, shortages, and increased costs. Prior literature has defined SC disruption differently. For instance, [13] categorized SC disruptions into two types – internal and external. Internal disruptions are related to the organization's own procedures and controls, while external disruptions arise from the external environment and stakeholders, and issues related to demand and supply. Scholars such as [4] reported SC disruptions that deal with delays in delivery from suppliers, bankruptcy, and the quality of raw materials. The risk of supply disruptions can be attributed to several factors, such as the complexity of products, operational ineffectiveness of suppliers, catastrophic situations, and insufficient coordination among SC partners [14-16]. Furthermore, too much reliance on suppliers also enhances the risk of SC disruptions, particularly when buyers have limited flexibility or alternative sourcing options [17]. [18] argued that a complex SC network with a probability of human errors increases safety concerns, leading to SC disruption. [19] presented the eight stages disruption cycle and connected the degree of organizational performance over time.

Therefore, the SC risk management concept was introduced which depicts a systematic analysis of SC disruptions throughout in identifying and addressing any issues related to SCs [4]. Prior literature has identified two main approaches to handling SC disruptions: 1) the anticipating approach, which assesses vulnerabilities and takes preventative measures, and 2) the resisting approach, which reacts and adjusts post-disruption processes. Mitigation strategies aim to minimize negative implications by identifying risks and selecting appropriate responses [20]. [4] introduced some strategies including cooperation, flexibility, redundancy, and control. The preparation phase involves resource allocation, organization, and short-term proactive measures [4,5]. End-to-end visibility is crucial for identifying anomalies, achieved through information sharing, performance tracking, and employing alert systems. [21] emphasized real-time access to reliable data, disruption analytics, and decision-making support. An effective response to disruption involves rapid resource allocation, active communication, and collaboration [4,5]. The recovery phase aims to restore normal SC operations. [22] defined recovery capability as coordinating resources to return to planned product flow. Strategies should stabilize and modify operations quickly to minimize long-term impacts and maintain continuity [23]. Emergency purchases from unaffected suppliers and partial product type changes can help during prolonged disruptions [24].

Scholars such as [25] described supply chain resilience (SCR) as the ability to handle unexpected disruptions, emphasizing proactive measures over reactive ones. Several scholars have noted that resilience in SCs involves adapting to disruptions and quickly resuming performance [3,4]. [26] formalized resilience as the capacity to anticipate, respond to, and recover from disruptions while maintaining operational continuity and control. Prior literature has defined SC resilience in different ways. For instance, [27] explained that SC resilience encompasses the ability to continue, recover, and restart operations after a disruption. It refers to the capacity of complex industrial systems to endure, grow, and adapt

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in the face of adversity. SC resilience involves a proactive, organized, and integrated approach to managing SC capabilities for unforeseen events, not just recovery from accidents [28]. SCR ensures the SC can respond to adverse consequences and uphold its goals [26]. Resilience involves a multi-stage process with two key phases: resistance and recovery, each with distinct strategies and procedures. In the resistance stage of the SC, the goal is to proactively prevent disruptions or minimize their impact. This begins with utilizing risk analytics and preventative measures to identify vulnerabilities and potential threats [29]. This phase is crucial for reducing the negative impacts of disruptions and protecting operations, reputation, and client relationships. The recovery phase follows, focusing on restoring normalcy and optimizing operations. Stabilization is the first step, aiming to restore functionality and ensure SC activities regain their footing. Flexibility and adaptability are key during this phase, allowing supply networks to recover from shocks. The return stage prioritizes maximizing operations and recovering lost ground. Efficient data analytics and technology use are essential here [30]. By leveraging data-driven insights and technical capabilities, companies can swiftly restore full operational capacity. This requires assessing performance, identifying problem areas, and applying lessons learned from past disruptions. Prior research highlighted the importance of a proactive approach to risk mitigation through avoidance and containment, rapid detection and damage control, adaptation and flexibility, evidence-based decision-making, and the strategic use of technology. A holistic strategy that covers all these phases ensures the continuous flow of goods and services and maintains market competitiveness in an increasingly complex and unpredictable business environment.

2.2   Data analytics as a driver of SC resilience

Data analytics involves gathering, processing, and analyzing large sets of data to uncover meaningful insights using advanced tools like machine learning, data mining, and predictive modeling. It identifies patterns, trends, and relationships within the data. SC data analytics uses these techniques to enhance SC operations and decision-making. By analyzing data from suppliers, customers, logistics providers, and internal systems, companies gain valuable insights into performance, uncover risks and opportunities, and streamline processes. This improves visibility, agility, and resilience, enabling better responses to disruptions and market changes. Data analytics functions are categorized into four types: descriptive, diagnostic, predictive, and prescriptive. [31] stated that descriptive analytics helps infer lessons from past events, identifying issues and opportunities in processes. It extracts information from large datasets to determine "what is happening?" in project management contexts. Predictive analytics answers "what will happen" by forecasting demand using historical data [31]. It uses mathematical methods and programming techniques to predict future events and explain why they might occur. Prescriptive analytics, based on descriptive, predictive, and optimization models, generates decision recommendations, answering "what is expected to happen?" [32]. It assesses possible decisions using mathematical models and advanced statistical methods [33]. Similarly, diagnostic analytics answers "what caused this to happen?" [32]. It identifies underlying causes of issues or patterns in both historical and current data, offering insights to inform future decisions, such as why SC shipments were delayed, or sales targets were unmet.

The integration of data analytics into SCs is proving to be transformative in today's corporate landscape. Given the complexity and unpredictability of global SCs, risk management has always remained a central concern across the discipline. Building trust within supply networks, as highlighted by [34], involves a company's ability to forecast, manage, and recover from operational disturbances. This concept serves as the foundation for the connection between data analytics and SCR. Improved SC visibility is crucial for resilience. Data analytics enables organizations to monitor, evaluate, and predict disruptions in real time, making anticipation a key stage of resilience. Beyond predictions, data analytics enhances scenario planning, a risk management technique that involves creating and examining possible situations. Organizations can thrive in an unstable world by making data-driven decisions, predicting disruptions, and responding effectively. Data creates value by enabling transparency, fostering experimentation, supporting customization, driving automated decision-making, and promoting innovation in business models, products, and services. The interpretation of business data enhances the value of analytics, and its timely presentation to decision-makers is crucial for effective decision-making [35]. The true potential of big data is realized when it informs decision-making. Predictive analytics is needed for short-term demand forecasting, considering patterns and seasonality [36]. Improved forecasting enhances risk management, benefiting supply risk management through data collection, analysis, and risk identification [37]. Both predictive and prescriptive analytics aid strategic decision-making [38]. Data analytics addresses issues in SC structure, organizational culture, sourcing decisions, and product/service design and development [36]. Using data analytics enhances the discovery of insights, leading to improved risk management and better corporate performance.

2.3   Descriptive analytics as a tool for proactive resistance in SC resilience

The Resistance Phase is crucial for maintaining uninterrupted operations during disruptions. Its main goals are to prevent, mitigate, and manage risks and vulnerabilities. Descriptive analytics enhances SCR by using real-time and historical data to inform decisions, helping companies manage obstacles during this phase. Descriptive analytics is vital for risk assessment, as it identifies potential weaknesses and risks in the SC. This information allows companies to proactively address and mitigate these risks. It also plays a key role in resource allocation, enabling informed decisions

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based on past performance data [39]. By optimizing resource allocation, businesses can ensure operational continuity during disruptions. By using past and present data, organizations can mitigate risks and strengthen SCR, ensuring the smooth flow of goods and services while enhancing market competitiveness. In an era of ongoing SC disruptions, descriptive analytics is essential for proactive resilience, enabling companies to overcome challenges and meet consumer needs sustainably.

2.4 Descriptive and diagnostic analytics for effective response to SC disruptions

The Containment stage within the Resistance Phase of a robust SC focuses on controlling and mitigating disruptions. It aims to prevent disruptions from escalating and to minimize their impact. Descriptive Analytics forms the basis for containment strategies by analyzing past and present data to highlight SC vulnerabilities and emerging disruptive trends [40]. Identified vulnerabilities are further examined using Diagnostic Analytics to uncover the root causes of disruptions. By analyzing historical and current data, diagnostic analytics can pinpoint the fundamental factors behind disturbances. Understanding this, firms can develop containment strategies, such as collaborating with suppliers to increase production or diversifying supply sources [40]. Together, Descriptive and Diagnostic Analytics offer a comprehensive view of SC vulnerabilities and their underlying causes. This enables proactive, accurate, and effective containment strategies to mitigate disruptions during the Resistance Phase.

2.5 Diagnostic and predictive analytics in response and recovery phases: enabling stabilization

The Stabilization step in the Recovery Phase is crucial for resuming normal operations on track and ensuring overall organizational stability after a disruption. During this period, diagnostic analytics proves its efficiency by examining historical and real-time data to uncover the root causes of disruptions. These insights enable companies to make informed decisions to swiftly resolve and mitigate long-term risks, enhancing SCR and reducing future disruptions. When combined with diagnostic analytics, predictive analytics add value by focusing on future outcomes. It uses historical and real-time data to forecast potential disturbances and their impacts, allowing proactive measures to prevent or mitigate disruptions. The true power lies in the synergy between diagnostic and predictive analytics. Diagnostic analytics identifies and analyzes the root causes of problems, while predictive analytics forecasts potential future issues. This combination significantly supports SC recovery and safeguarding operations against future disruptions [19]. Together, diagnostic and predictive analytics ensure SC stability during the Response and Recovery stages. Predictive analytics provides insights to support proactive decision-making, while diagnostic analytics retrospectively examines disruptions for improvement [41].

2.6 Prescriptive analytics: enhancing SC resilience through data-driven approaches

The Return stage in the Recovery Phase marks the final step in overcoming a disruption and resuming normal operations. Prescriptive analytics, the most advanced form of data-driven SCR, enables strategic planning and enhancement of operations. It goes beyond descriptive and diagnostic analytics by providing actionable insights and recommending optimal strategies to improve resilience. Using historical and real-time data, prescriptive analytics enables informed decision-making, helping businesses to proactively respond to disruptions. Prescriptive analytics is crucial for quick reactions to disturbances, assessing various scenarios, and determining the best recovery strategies. It helps reduce the impact of disruptions by rerouting shipments, adjusting production schedules, and reassessing relationships with suppliers. Additionally, it fosters a culture of continuous improvement, constantly refining plans, and processes, and learning from past disruptions. In a dynamic SC environment, prescriptive analytics offers real-time decision support, enabling flexible, data-driven choices as conditions evolve. During the Recovery Phase, prescriptive analytics optimizes resource allocation, leverages technology, and provides adaptive solutions to effectively restore full operational capabilities [41].

We aim to illustrate the complex relationship between data analytics methodologies and the key stages of an effective SC. Figure 1 serves as a roadmap, guiding us through the strategic use of descriptive, diagnostic, prescriptive, and predictive analytics at each step of building a resilient SC process. The analysis will explore how analytics technologies help firms effectively manage disruptions and enhance their SCs in a complex and rapidly changing business environment.

3 Methodology

This research employs a qualitative multi-case study approach. Qualitative research explores social phenomena by exploring prevailing viewpoints, and their application in everyday activities. Case study, a form of qualitative research, provides realistic, dynamic, and personal insights to a deeper understanding of complex business problems. Case studies not only provide an in-depth understanding but can also generate hypotheses and be conducted either once or multiple times, examining phenomena from the perspective of the participants [42].

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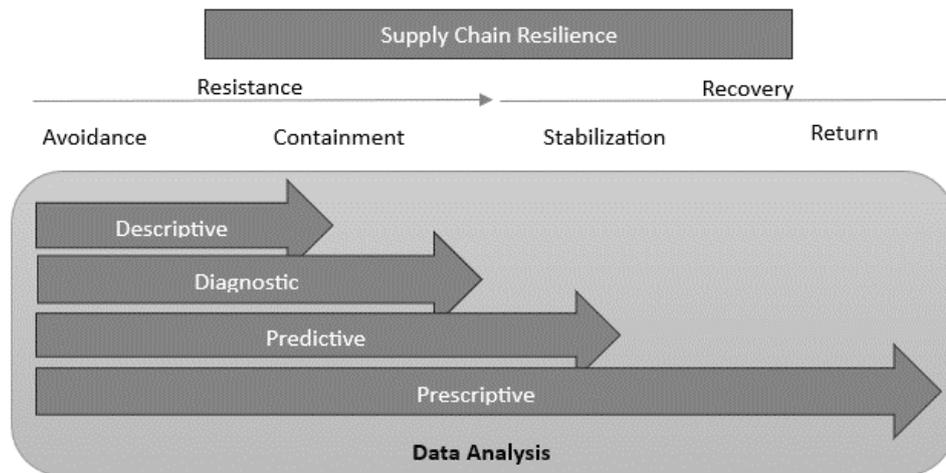
Figure 1 Conceptual framework of data-driven SC management

3.1 Data collection

The study aims to examine how businesses integrate data analytics into various phases of SCR. Purposive sampling principles were used to select the study's sample, allowing for the exploration of research themes while maintaining diversity for comparative analysis. The selection criteria are influenced by the study's goals, existing knowledge, theories, potential hypotheses, or knowledge gaps [43]. Case companies were selected based on their product offerings and business models, specifically involving electronic products and components in their SC operations. Interviewees were chosen based on their experience with data-driven processes and their roles related to SC operations. Six case companies with seven SC experts participated in semi-structured interviews in 2023. These interviews lasted between 35-57 minutes. These case companies belong to various sectors, ranging from medium to large sizes. To maintain confidentiality, each company is assigned an identity reflecting their specialty or industry. Purposive sampling guided the selection of these organizations, representing different degrees of data-driven execution and various industries. To ensure a broad range of viewpoints, we selected firms that vary in both industry type and size, as shown in Table 1.

Table 1 Overview of case interviews

Number	Industry	Interview's position	Experience (years)	Interview duration
1	Telecommunication	Delivery Manager	6	52 minutes
2	Automobile Factory	Logistics Director	12	46 minutes
3	Electronics Manufacturing	Manager in Operational and Supply Chain	8	53 minutes
4	Health Care Devices and Applications	Procurement Manager	8	57 minutes
5		Planning Manager	6	51 minutes
6	Retail in Spare Parts and Accessories to Home and Leisure Products	Commodity Manager	11	49 minutes
7	Digital Appliance Device Manufacturer	Head of Procurement	20	35 minutes

3.2 Data analysis

This study utilizes thematic analysis in conjunction with [44]'s five-step qualitative data analysis framework to rigorously analyse empirical data. This approach facilitates the identification of key themes within large qualitative datasets, enabling effective communication of important findings. The analysis process begins by organizing data into a structured database. Notes and recorded material are carefully arranged for easy access and organization. Interview audio is transcribed and systematically categorized in Excel, using a matrix format, where each column represents a firm case, and each row corresponds to emerging themes or codes. The second stage involves breaking down the material into smaller, manageable chunks and exploring new labels or "codes" to these segments for deeper analysis. Thematic analysis relies on coding as a means to systematically index the data and identify important topics. [45] suggest template analysis as a coding strategy, which involves creating a flexible coding template from a subset of data, which can be refined iteratively to reflect the complexity of the entire dataset. The study applies deductive coding and investigates themes derived from the conceptual framework that guided the formulation of interview questions. [42] suggest that codes

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emerging from empirical data enhance the objectivity of qualitative analysis. [45] recommend using priori themes sparingly with ongoing re-evaluation and removal as needed.

Next, the data is rearranged and recombined to reveal underlying patterns and connections after the initial identification of recurring themes and codes. By employing this technique, disruption management strategies across firms can be effectively compared. Excel provides an effective platform for organizing interview quotes according to thematic categories. [44] recommends using two-dimensional matrices, a method well-suited to this analytical approach. The final steps involve interpreting the data and drawing conclusions based on the identified patterns. The data is evaluated to identify the most significant analytical insights, and results may be rechecked for completeness and accuracy. The findings are compared against existing theories to assess their practical applicability. These findings are organized into key topics in the subsequent sections of the paper. The synthesis of conceptual insights, empirical evidence, and answers to research questions leads to conclusions that summarize the study and offer meaningful insights.

4 Results and discussion
4.1 Data analytics enabling SC resilience
4.1.1 Avoidance

SC analytics are systematically applied during the Avoidance stage to build a resilient SC. The process typically begins with descriptive analytics, which involves examining historical data to understand past patterns and disruptions. This early detection plays a crucial role in timely and proactive preparation against potential shortages or disasters. For example, in the Automobile case, the respondent mentioned that they use data analysis to investigate recurring issues, often caused by transportation routes or customs procedures. Similarly, the Healthcare case highlighted how past inventory and shortage records help in understanding why certain products are consistently unavailable, enabling them to confidently address and resolve the issue.

Identifying and mitigating shortages involves coordination among various SC stakeholders, including suppliers and subcontractors. Most firms receive regular updates on component availability and purchase order status from their manufacturing partners and suppliers, often weekly. Staying updated and devising alternative strategies is essential. A comparison analysis is conducted to align findings with actual needs and priorities. This approach is reflected in the Electronics Manufacturing case, where the respondent stated "We have weekly reviews with our supplier to ensure our needs, and their supply are aligned. Instant updates allow us to respond quickly and minimize potential disruptions." Together, these cases highlight how proactive data use and close supplier collaboration enhance SC resilience during the Avoidance stage. To further support this point, Table 2 provides an overview of the typical benefits firms gain from using data analytics to mitigate disruptions, with sample quotations from various firms.

Table 2 Advantages and illustrative quotes

Advantage	Illustrative quotes
Alignment	*"Keeping our information up to date is important for both us and the supplier. It allows us to ensure that we are aligned with each other's needs and abilities."* (Case - Retails) *"Making sure that everyone understands the same information is important because it reduces the chances of miscommunication or misunderstandings."* (Case - Digital Appliance)
Responsiveness	*"Having instant updates allows us to promptly respond to any changes or unexpected events that may occur in the supply chain."* (Case - Automobile) *"Being flexible is really important when it comes to dealing with disruptions quickly*." (Case - Electronics Manufacturing)
Disruption Mitigation	*"Visualizing vendor capacity and scheduling help us anticipate and minimize disruptions, lowering their effect on operations."* (Case - Retails)
Prioritization	*"The supplier's capacity and schedule in their coverage table allows us to alter our priorities depending on, ensuring most important demands are covered even with limits*." (Case - Automobile)
Efficiency	*"Current information helps us to improve decision-making. Based on current data, we may allocate resources and change production plans*." (Case - Electronics Manufacturing) *"We use data analytics tools to analyze historical sales data and customer demand patterns. Based on this analysis, it appears that certain products tend to be more popular during times of the year*." (Case - Automobile)
Relationship Building	*"Maintaining open and honest communication, as well as sharing data regularly, can help foster a stronger relationship between your company and the supplier. Fostering trust and collaboration is important because it can greatly benefit long-term partnerships*." (Case - Healthcare)

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Thus, it is reasonable to say that data analytics serves as both an investigative and anticipatory tool for optimizing SC operations. It helps identify and proactively analyze potential disruptions, provides insights into supplier performance during crises and enables informed decision-making for resource allocation and emergency response measures.

4.1.2 Containment

Containment is an alternative strategy to avoidance, crucial for mitigating the spread of disruptions and minimizing their impacts. This capability enables companies to respond promptly and decisively, reducing negative effects on operational efficiency, reputation, and customer relationships. Data pipelines and reporting systems provide real-time visibility, enabling companies to quickly adjust their strategies in response to emerging issues. For example, in the Automobile case, the respondent shared, "*One thing we're currently working on is using technology to enhance visibility and transparency throughout SCs. It's all about finding ways to make things clearer and easier to understand. This can really help us identify and address risks faster and more effectively.*" In the Electronics Manufacturing case, real-time monitoring played a key role during a disruption, with the respondent highlighting its importance by stating, "*During the disruption, we kept a close eye on real-time data, including online sales, customer inquiries, and social media sentiment. We also monitored the progress of component shipments from the supplier.*" Similarly, in the Healthcare case, automation supported early intervention, with the respondent explaining, "*We have developed a system that automatically sends alerts whenever inventory levels of important components or finished products fall below a specific threshold. These alerts notify inventory managers and procurement teams to take necessary actions to avoid stockouts or production disruptions.*"

During containment, data interpretation is crucial for scenario planning. Examining historical data provides significant contextual information, helping companies identify trends, patterns, and past events that could influence future situations. For example, in the Electronics Manufacturing case, the respondent explained, "*Historical and real-time shipping data helps us analyze shipping trends and risks. We assess routes, logistics vendors, and transportation methods, which might include establishing alternate shipment paths, backup logistics partners, and stockpiling finished goods in crucial locations.*" Similarly, the respondent from the Telecommunication case highlighted how trade tensions disrupted semiconductor SCs, mentioning, "*Due to trade tensions between two important suppliers, semiconductor SCs are disrupted. We record their component SC, discovering alternate vendors and storage options. Our analysts use data analytics models to study the impact of a component supply disruptions, including manufacturing delays and potential price increases.*" In the Digital Appliance case, scenario analysis was used as a proactive planning tool, as reflected in the respondent's statement, "*We have been exploring hypothetical situations for our business, which we refer to as scenario analysis. This tool helps us prepare for unexpected circumstances by examining various scenarios and their potential impact on our SC.*"

These examples illustrate how, during the containment stage, combining historical and real-time data with scenario planning enables firms to anticipate disruptions and develop robust containment strategies. Table 3 presents a comprehensive analysis of the benefits associated with using data analytics in the SC, focusing on enhancing resilience during the containment phase.

Table 3 Empirical findings: Data-driven benefits in Containment Stage

Advantage	Illustrative quotes
Rapid Detection	"*As soon as the system notices a significant decrease in stock for a popular product, it promptly sends out alerts to restock the inventory. Rapid detection is beneficial because it helps prevent situations where there is a shortage of stock and customers are left unsatisfied.*" (Case - Digital appliance)
Precise Isolation	"*We can isolate and recall a batch of items if a manufacturer's quality control data analytics find errors. This accuracy avoids mass recall, saving time and money.*" (Case - Digital Appliance)
Visibility	"*Delivery records such as delivery date and time helps identifying delays and route deviations early, enabling quick reactions to disturbances.*" (Case - Electronics Manufacturing)
Robustness	"*We use past data to identify providers with late delivery or quality concerns. Data analytics may help a corporation diversify its supplier base for a more dependable supply of goods.*" (Case - Retails)
Agility	"*Data-driven demand forecasting methods can predict seasonal demand surges. With this knowledge, we can immediately alter production and inventories to suit client demands without delays or shortages.*" (Case - Digital appliance)
Velocity	"*Integrating data analytics into inventory management systems enables real-time stock and order changes.*" (Case - Retails) "*This information speeds up our order processing and delivery, ensuring things flow quickly through the SC.*" (Case - Automobile)

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Case firms leverage SC data analytics to build resilient networks that ensure the continuation flow of products and services. Historical descriptive analytics improve visibility and robustness, diagnostic analytics enhance resilience and agility by identifying root causes, predictive analytics forecast disruptions, and prescriptive analytics provide effective solutions. This multifaceted approach enables organizations to develop resilient supply networks, boost performance, and minimize disruptions.

4.1.3   Recovery

Stabilization is the initial phase within the Recovery Phase of SCR. Following the disturbance, the primary objective is to restore stability and reinstate regular operations. Reconfiguration may play a crucial role in this process, including adjustments to supplier relationships, transportation networks, or industrial infrastructure to efficiently recover from the impact and re-establish operational continuity. In the Stabilization phase, addressing disruptions through redundancy measures in key components of the SC is advisable. Redundancy measures serve as a safeguard in the event of primary system failure, thereby enhancing overall operational stability.

Predictive analytics is crucial for supporting supplier diversification, providing valuable insights and forward-looking projections. These tools help firms make well-informed decisions about supplier selection and diversification plans, as noted in the Automobile case, "*When customized components are important and expensive to replicate, predictive analytics can evaluate risks of relying on a single supplier. By anticipating disruptions and understanding their impact, we can create backup plans and ensure we have essential components in reserve.*"

Flexibility and adaptability are fundamental attributes of a resilient SC, especially during the Stabilization phase. This phase aims to restore normal operations after disruptions. Data analytics, when combined with a data-driven methodology, plays a significant role in enhancing these attributes. These capabilities enable organizations to adjust operations in real-time, reassess priorities, and reconfigure SC components as needed to respond effectively to changing post-disruption conditions. Table 4 summarizes how data analytics contributes to improving SC stability during the Stabilization phase, outlining key benefits and illustrating how various analytics approaches support flexibility, adaptability, and recovery.

Table 4 Data analytics improving SC stability

Attributre	Illustrative quotes
Real-time Demand Forecasting	"*Data analytics allows us to accurately predict and stay updated on demand, ensuring that SC activities align with changing consumer needs.*" (Case Retails) "*Having flexibility helps to reduce the chances of having too many inventory or not enough inventory.*" (Case - Automobile)
Inventory Optimization	"*When it comes to predictive analytics, we have developed a Bayesian method that helps us determine the best inventory levels. We do this by analyzing past data and current market trends. Being flexible in this way allows for the ability to maintain low inventory levels while still making sure that products are easily accessible.*" (Case - Automobile)
Supplier Performance Monitoring	"*Using data analytics, we can constantly monitor the performance of our suppliers. When there are disruptions, being adaptable helps us find other sources or change our procurement strategies so that our SC keeps running smoothly.*" (Case - Healthcare)
Efficient Production	"*Predictive analytics is a tool that allows us to make better production schedules by using up-to-date data and predictions of customer demand. The ability to adapt ensures that manufacturing processes can stay efficient, even when unexpected disruptions occur.*" (Case - Electronics distributor)
Scenario Analysis	"*Data analytics helps us analyze different scenarios to understand the potential effects of various strategies. We can use this adaptability to assess and execute the most effective plan of action by utilizing real-time data.*" (Case - Automobile)
Customer Insights	"*Using a data-driven approach allows us to gain a thorough understanding of what customers want and expect. We can enhance customer satisfaction by adjusting our products, services, and delivery methods to meet the changing needs of our customers.*" (Case - Digital appliance)
Risk Mitigation	"*Predictive analytics helps to identify possible risks and disruptions in the SC, allowing companies to take proactive measures to mitigate these risks. Our ability to adapt allows us to respond swiftly to new threats and take proactive steps to prevent them.*" (Case - Healthcare)
Resource Allocation	"*Predictive analytics helps in making resource allocation more efficient by ensuring that resources are allocated effectively to meet the changing demand, while also minimizing any unnecessary waste. The ability to adapt helps to lower the costs of operations.*" (Case - Healthcare)

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4.1.4   Return

The "Return" phase in SCR is crucial for enterprises, focusing on the rapid restoration of full operating capacity following a disruption. During this phase, prescriptive analytics plays a vital role in enhancing SC robustness. Analytics guide the recovery stage using diverse techniques. Diagnostic analytics are particularly useful for in-depth analysis of disruptions, helping identify root causes, and providing recovery guidance. This analysis framework improves readiness and recovery from future disruptions. For example, in the Health case, the respondent explained, "*Next year's sales margin estimate is determined using prescriptive analytics. We analyze market trends, competition intelligence, and historical sales data. Operational business units set sales and profitability objectives for product groups. Monitoring progress allows timely strategy adjustments.*"

Similarly, the Electronics Distributor case highlights, "*Data-driven pricing models help determine effective prices for products and services, maintaining profitability even in difficult circumstances. Increased revenue streams create a stable and resilient financial situation.*"

Predictive analytics offers actionable recommendations for decision-making and resource allocation, by considering various constraints, objectives, and historical data. These insights help accelerate recovery and mitigate the impact of disruptions. An effective learning and growth plan is essential during the Return phase to guide recovery and strengthen against potential disruptions. For example, in the Telecommunication case, the respondent explained, "*When reaching the Return phase, we use historical data to identify areas for strengthening resilience and implement innovative measures.*" Similarly, in the Automobile case, the respondent highlights, "*We delve into what happened to identify weaknesses. Setting up classes or training events where people share their learnings fosters a mindset of continuous improvement.*"

4.2   Risks in data-driven resilience

Case companies encounter various risks and complexities in building data-driven SCR. Risks related to data quality, unexpected results, SC complexity, and accessibility are explored here. For example, in the Retails case, the respondent mentioned that "*Retailers gather significant data from various sources, including point-of-sale systems, customer loyalty programs, and social media. However, this data can be fragmented and inconsistent, making it challenging to understand the SC comprehensively.*"

Analytical outcomes are often met with within companies due to concerns about data accuracy and reliability. Low-quality data leads to uncertain conclusions, inefficient decision-making, and potential vulnerabilities in the SC. For example, in Retail's case respondent, mentioned that "*Retailers frequently work with numerous suppliers, making it challenging to gather all necessary data for a complete SC understanding.*" Similarly, the respondent from the Electronics Distributor case pointed out "*Data gathered from sensors on machines, production lines, quality control systems, and customer feedback can be noisy and incomplete, making it difficult to spot trends and patterns*". Also, the respondent from the Healthcare case explained that "*Healthcare device SCs undergo extensive regulation and adhere to demanding quality standards. Regulatory changes or product recalls can disrupt operations and create vulnerabilities.*"

A major barrier to establishing a data-driven culture in SCs is the lack of data integration, over-reliance on experience, and resistance to change. For example, the respondent from the Electronics Manufacturing case pointed out "*It's frustrating how departments work in silos, making decisions without considering data from other areas. They miss out on the bigger picture. It would be better if they had a broader viewpoint*". Similarly, the respondent from the Automobile case emphasized "*Decision-making power is often granted based on experience, leading employees to rely on past knowledge rather than analyzing current trends*". Resistance to change further complicates efforts, as described by respondent in Retail's case "*Employees hesitate to adopt new technologies or methodologies, feeling comfortable with current processes, even when data suggests changes could lead to improvements.*"

4.3   Summary of findings

The empirical results of this investigation address the research issues presented in the study. Firstly, the use of analytics on large volumes of data enables interviewed companies to anticipate and prepare proactively for disruptions. In the research companies reported employing predictive analytics to assess the likelihood of operational disruptions, allowing them to implement preventive measures in advance. This data-driven approach to decision-making emphasizes that SCR involves proactive planning and risk mitigation, not just reactive responses to unexpected events.

Furthermore, diagnostic analytics during the resistance phase plays a critical role in identifying vulnerabilities within the SC. The case companies demonstrated their ability to implement targeted measures aimed at protecting vulnerable areas and mitigating the negative impacts of disruptions. By addressing potential weaknesses before they escalate, companies enhance their overall resilience and effectively reduce their operational risks. Additionally, prescriptive analytics during the recovery phase contribute to the development of effective recovery strategies, optimal resource allocation, and informed decision-making processes. By enhancing flexibility and optimizing resource allocation, it enables companies to recover more rapidly and efficiently from disruptions. The research demonstrates that data-driven recovery efforts can significantly strengthen SCR, minimizing downtime and facilitating a fast return to normal

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operations. The results also highlight the competitive advantage of adopting a data-driven and integrated approach to resilience. A corporation's ability to withstand disruptions and navigate complex business environments distinguishes it from its competitors. Consistent with previous research, the findings suggest that leveraging data analytics to enhance SCR can provide a significant competitive edge in today's dynamic and interconnected global economy.

4.4 Discussion

This research confirms previous findings that using all analytical tools significantly impacts SCR [46,47]. Data-driven strategies help organizations predict, manage, and recover from disruptions, thereby enhancing overall operational resilience. Descriptive analytics provides a comprehensive understanding of current SC operations, serving as a starting point for measuring performance and identifying areas for improvement. This step is critical for mapping operational complexities and inefficiencies, optimizing their effects, and providing a solid foundation for subsequent analytical processes and optimization efforts.

During the resistance phase, diagnostic analytics plays a key role in identifying vulnerabilities within the SC by thoroughly analyzing both historical and real-time data. This approach helps organizations to pinpoint weak points and sources of risk, allowing strategic resource allocation to strengthen these areas and reduce disruption impacts. Integrating descriptive and diagnostic analytics improves the identification process, with insights derived from the descriptive phase enhancing the accuracy and depth of vulnerability identification. According to [48], organizations must proactively scan the environment and adapt to both internal and external changes to maintain resilience and competitiveness. Predictive analytics builds proactive resilience by forecasting potential future events and their associated impacts. The case companies examined in the study use both historical and real-time data to forecast potential disruption, allowing them to either prevent or lessen disruptions effectively. Predicting and preparing for disruptions helps businesses maintain smooth operations and reduce problem likelihood [29,49]. The integration of predictive analytics with descriptive and diagnostic data creates a comprehensive understanding of past, present, and future challenges, facilitating more informed decision-making.

Our findings demonstrate that performance insights from historical descriptive analytics enhance both robustness and visibility in SC. In parallel, diagnostic analytics uncover underlying causes of disruptions, promoting resilience and agility. Predictive analytics increases velocity and agility by forecasting disruptions. Prescriptive analytics expedites decision-making with a data-driven methodology. Collectively, these insights enhance visibility, improve problem diagnosis, enable disruption prediction, and support the development of effective solutions, ultimately building resilient SC networks. A multimodal strategy further maximizes efficiency and reduces disruptions across SC. The ability to respond rapidly during emergencies is crucial for SCR [19]. Predictive analytics, which analyzes historical and real-time data, helps predict potential disruptions, allowing organizations to respond proactively. Prescriptive analytics goes beyond offering specific, data-driven recommendations to mitigate their impacts, providing timely and effective responses. Delayed reactions to disasters can lead to substantial financial losses for companies and supply channels [49]. Response and recovery capabilities are critical for developing SCR [19,26,36]. Key organizational capabilities include promptly responding to environmental forces, reconfiguring resources, and recovering from vulnerabilities. Recovery is assessed based on cost, recovery time, disruption absorption, and mitigation power [19,26,29]. Predictive analytics optimizes resource allocation through suggested actions, ensuring coordinated and effective responses. Diverse data analytics techniques enhance SC resilience, especially during recovery. Descriptive analytics provides insights into past performance, aiding recovery process comprehension and enhancement. Diagnostic analytics identifies disruption root causes, facilitating targeted recovery strategies. Predictive analytics enables organizations to take proactive measures that reduce recovery time and costs. Prescriptive analytics builds on this by using real-time data to recommend optimal recovery strategies, ensuring that response efforts are both efficient and effective. Combining these technologies allows businesses to develop a comprehensive data-driven recovery plan, enhancing their ability to navigate the complexities of today's dynamic business environment. This integrated approach not only strengthens an organization's capacity to manage disruptions but also underscores the critical role of data analytics in building resilience. This leads to the first proposition:

Proposition 1: By effectively integrating various analytical tools, a company can enhance its ability to anticipate future events, mitigate risks efficiently, and maximize recovery measures. Together, these efforts play a crucial role in strengthening SC resilience.

Organizations can enhance resilience and adaptability by learning from past disasters. Continuous knowledge acquisition is crucial for developing creativity, flexibility, and resilience. Collecting insights from previous experiences helps mitigate the risk of losses due to disruptions. Unexpected disruptions highlight the need for a flexible SCR plan that can adapt to evolving challenges and uncertainties. In this study, data analytics is extremely significant for case companies. By accumulating substantial data and drawing from past experiences, these companies enhance their strategic approaches. Understanding previous disruptions strengthens SCR through the implementation of effective risk mitigation strategies. The case companies have shown that ongoing learning and adaptation make them more proactive, flexible, and resilient in the face of ongoing and future challenges. For the Telecommunication and Machinery Manufacturers, using

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data on bottlenecks and recovery times helps streamline recovery procedures, enabling quicker resumption of operations and more flexible SC architectures after disruptions. Each disruption and recovery instance presents learning opportunities.

Businesses may implement technology development and training programs as part of their risk mitigation strategies [50]. Training and development programs, especially those focusing on technical proficiency, equip SC professionals with the skills needed to effectively identify, manage, and reduce risks [51]. Acquiring information, learning from experiences, and drawing lessons from past events are essential for identifying and mitigating vulnerabilities [48]. During disruptions and recovery phases, data analytics significantly facilitate the process. These measures not only restore regular operations but also provide valuable information for developing and improving avoidance strategies. This two-way flow of information ensures weak spots are identified and recovery steps' effectiveness is studied, leading to changes that prevent similar disruptions from recurrence. Enhancing the avoidance phase involves seamlessly transferring recovery phase outputs forward. The case Retails has shown how data analytics directly inform the development of avoidance tactics. Such learning is critical for building greater resilience, reducing risk, and greater flexibility within the SC [52].

Incorporating a continuous, cyclical resilience strategy requires a committed data-driven approach to decision-making at every stage of the SC. Within this framework, benchmarking and experience-based learning serve as critical components of SCR [49]. Learning is essential in crisis management [53], contributing to enhanced resilience within a business and its SC. Resilience is not a static condition, but rather an ongoing commitment to proactive, evidence-based strategies. Insights gained from one cycle serve as input for the next, enhancing avoidance strategies. In conclusion, SCR as a continuous, data-driven process is vital in a rapidly evolving business environment. Firms need agile and adaptable approaches to respond to unforeseen circumstances. By acquiring valuable information during each phase of disruption and recovery, organizations can continuously enhance their SCR, improving both resilience and operational effectiveness over time. This leads to the second proposition:

Proposition 2: SCR is not a one-time effort but an ongoing commitment, requiring data-driven adaptable policies at every stage of the SC.

While SC analytics improve resilience, they also have drawbacks. Success depends heavily on proficiency in Data Analytics, which requires active involvement from senior management. Factors affecting the impact of Business Data Analytics on SC effectiveness include strategic alignment [54], recognition stage [55], supplier base complexity [56], and supply uncertainty. Our findings from the cases in "Electronics manufacturing", "Automobile", and "Retail" reveal challenges in creating a data-driven culture, such as resistance to change, reliance on past experiences, and lack of data integration. Addressing these constraints is crucial for fostering a robust and efficient SC through effective data analytics. Experts must align their data analytics knowledge with the organization's strategic objectives. Adopting data-driven approaches requires a cultural transformation toward data-driven decision-making. This shift involves optimizing data analytics benefits, considering risk reduction strategies, and integrating analytics into the core business culture.

Traditionally, SC decisions relied on intuition, experience, or established norms. Transitioning to data-driven methods requires strong leadership commitment to support this shift. Organizations must foster a data-driven culture that enables informed decisions at all levels [56]. Comprehensive training programs are essential for closing the knowledge gap across all business functions, including SC management, procurement, and logistics. These programs should aim to equip individuals with skills to interpret data, analyze insights, and effectively use analytical tools to support informed decision-making. Overcoming resistance to change requires efficient change management techniques led by advocates of data-driven methodologies, fostering a collaborative and adaptable culture. To ensure a smooth transition to data-based decision-making, leaders must proactively address concerns, allocate necessary resources, and provide ongoing support. Ongoing development and learning are crucial in a data-driven culture. Organizations should include feedback loops in their decision-making process, enabling them to regularly evaluate outcomes and modify plans based on acquired knowledge. Extracting insights from past disruptions and integrating them into future decision-making is essential for developing SCR. This leads to the third proposition:

Proposition 3: Organizations must undergo a significant cultural transformation to fully adopt data-driven decision-making. By leveraging data analytics, they can effectively mitigate risks and strengthen SC resilience.

4.5   Framework for data-driven SC management

The shift from traditional, linear SC analytics to a resilience-focused approach underscores the need for flexible, data-driven strategies at every stage of the SC. Resilience is now seen as a continuous commitment, requiring various data analytics methods (prescriptive, predictive, diagnostic, descriptive) to improve SC resilience. Firms with strong data analytics capabilities are better positioned to identify disruptions, reduce risks, and enhance recovery processes. Analytics should be applied comprehensively across all phases to ensure continuity and readiness. Proactive risk mitigation and continuous adaptation based on data insights are crucial for outperforming conventional, linear processes. Prescriptive analytics, the most advanced form of data analysis, offers significant advantages by recommending optimal actions. However, it remains underutilized due to its high demands on IT infrastructure, skilled human resources, and advanced modeling capabilities. To address these challenges, the study proposes a flexible framework (see Figure 2) that adapts to

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practical constraints by prioritizing alternative analytical methods more suitable for the specific needs of the investigated firms. This approach enhances the efficiency and feasibility of using data analytics in SCs while ensuring the integration of data-driven decision-making at every stage of the SC process.
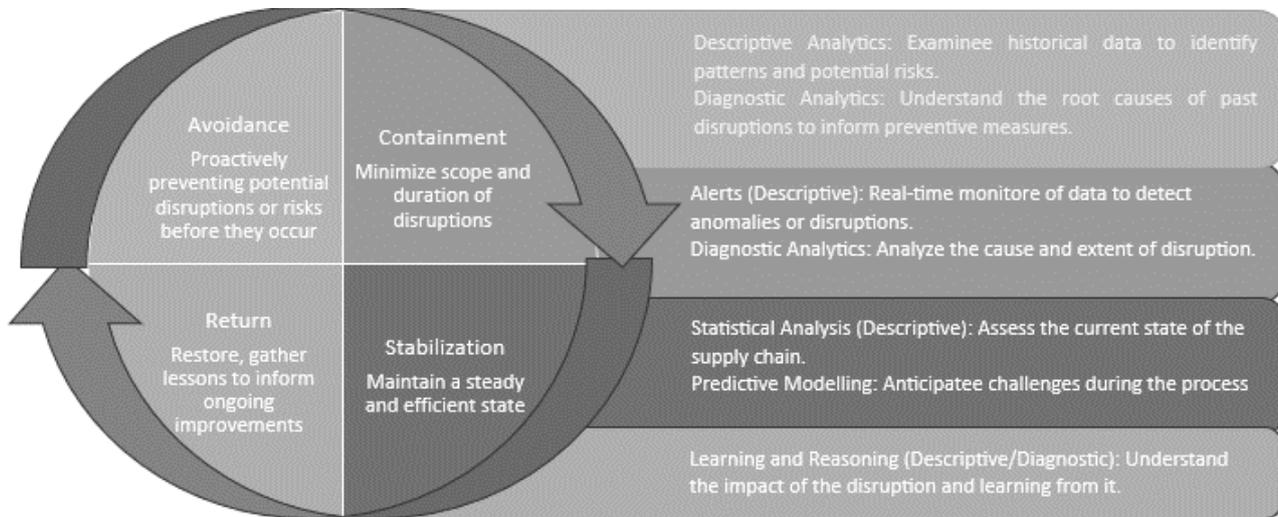
Figure 2 Modified and elaborated Conceptual framework for Data-Driven SC management

5   Conclusions

This research aimed to explore SC data analytics theories and their role in building resilience. It examined how resilience can manage supply disruptions and assist firms in dealing with them effectively. The research provided valuable insights into how data analytics strengthens SCR, drawing on real-life examples from various industries. It explored key areas like risk management, demand forecasting, and inventory optimization, demonstrating how data analytics make SCs more adaptable and resilient to disruptions. Additionally, the study examined methods for effectively implementing data analytics in SCs, considering theoretical frameworks and real-world case studies. It discussed the most effective approaches, identified key obstacles, and discussed strategies for successfully integrating data analytics into SC management systems.

5.1   Theoretical and managerial implications

This study addresses gaps in SCR by linking data analytics to every stage of the resilience cycle. It integrates data analytics throughout the SCR processes, outlining both the advantages and disadvantages of adopting data-driven SC approaches to resilience. The study examines the positive and negative aspects of incorporating data analytics at each stage of SC and offers practical recommendations for companies looking to enhance resilience through data-driven decision-making. The study fills gaps in the literature on data analytics and SC resilience, as noted by [7-10]. Previous studies have highlighted the importance of integrating descriptive and predictive analytics into prescriptive models. However, fully understanding the benefits of data-informed decision-making at each stage of the resilience cycle has remained challenging. By addressing these gaps, this research advances the field with a comprehensive analysis of practical data analytics at different stages of SCR. It provides an authoritative framework for utilizing data analytics to enhance SC operations effectively, closing gaps identified by [8]. The study offers a comprehensive data analytics framework for SCR, derived from empirical data and analysis. It provides a clearer understanding and actionable recommendations for organizations seeking to adopt a resilient, data-driven approach to strengthen their SCs.

The qualitative analysis of data analytics in enhancing SCR has significant managerial implications. Firstly, the research underscores the importance of data-driven decision-making, enabling managers to better navigate uncertainty more effectively, allocate resources strategically, and adjust their strategies to evolving conditions, thereby improving operational resilience. Secondly, the findings emphasize the importance of proactive risk mitigation. Data analytics enables managers to identify vulnerable areas within the SC, allowing for strategic resource allocation and proactive problem resolution, both of which are crucial in navigating a turbulent business environment. Lastly, the research highlights the need for organizational flexibility and continuous learning. Managers should foster a culture of ongoing learning, ensuring employees are equipped to effectively use data analytics tools, stay updated about technological advancements, and implement the industry's best practices. This commitment to learning and flexibility enhances overall resilience and competitiveness.

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5.2 Limitations and future research

This study has inherent limitations due to its qualitative approach. Qualitative methods, such as interviews and case studies, may be biased by the personal interpretations of a small, selected group, which could potentially limit the comprehensive evaluation of data analytics' impact. To gain more robust evidence, future research could benefit from quantitative analysis using a larger dataset. The study's generalizability is also limited by industry, location, and company-specific factors, which may not fully represent the broader landscape of SC scenarios. Additionally, the financial implications of implementing data-driven approaches are often overlooked. Assessing the costs of technology implementation, data procurement, training, and system maintenance is crucial, especially for smaller or medium-sized businesses. Future research should combine both quantitative and qualitative methods, including a wide range of industries, and perform comprehensive cost-benefit analyses. Continuous studies could capture the evolving impact of technology over time, and comparative analysis across companies can uncover effective strategies and challenges, further deepening our understanding of data analytics can strengthening SC resilience.

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Optimizing logistics and production flows for sustainability in green flexible job-shops

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Abstract: In industrial operations, the effective optimization of logistics and production flows, including material, energy, and information flows, is essential for improving operational performance while reducing environmental impacts. The combinatorial complexity of the green flexible job-shop scheduling problem (GFJSP) and its connection to sustainable manufacturing have attracted significant attention in recent research. This study aims to minimize total flow time and carbon emissions by optimizing the management of industrial flows, while accounting for technical elements of logistics such as production sequencing, resource allocation, and coordination of material and energy flows. Two complementary solution approaches are proposed: an exact constraint programming (CP) model for small-sized instances, ensuring optimality, and a particle swarm optimization (PSO) algorithm enhanced with an energy-aware encoding scheme and logistic map-based population initialization for medium and large-scale problems. Numerical experiments demonstrate the effectiveness of both approaches in addressing operational efficiency and environmental objectives. The novelty of this work lies in integrating the management of logistics and production flows with sustainable scheduling through a hybrid exact–metaheuristic strategy. Sensitivity analysis further validates the robustness of the PSO, highlighting how exact and metaheuristic methods complement each other to tackle complex industrial scheduling challenges. Overall, this study provides both scientific insights and practical guidance for managing logistics and production flows in sustainable industrial systems.

1 Introduction

Efficient management of material, energy, and information flows is vital to manufacturing performance, impacting productivity, lead times, and environmental sustainability. The flexible job-shop scheduling problem (FJSP) represents one of the most complex combinatorial optimization challenges due to its dual decision layers: machine assignment (routing), where operations can be processed on multiple eligible machines, and operation sequencing [1]. This dual-layered structure makes the FJSP a strongly NP-hard problem, even more challenging than the classical job-shop scheduling problem [2]. Traditionally, the FJSP has been addressed with the primary objective of minimizing the makespan [3], but recent industrial and environmental concerns require considering multiple flows and their management throughout the production system. In particular, minimizing total carbon emissions has become increasingly critical, in line with the principles of green manufacturing, low-carbon production planning, and sustainable logistics [4]. The industrial sector remains one of the major contributors to greenhouse gas emissions. For instance, the manufacturing industry accounts for about 30–35% of global energy use and nearly 40% of total CO_2 emissions worldwide [5]. In recent years, most research on FJSP has emphasized traditional performance indicators, such as makespan, tardiness, and machine utilization, while paying limited attention to environmental and flow-oriented concerns. Although the FJSP reflects the complexity and flexibility of real industrial environments, sustainability-oriented criteria, particularly carbon emission reduction and total flow time minimization, have rarely been addressed together in this context. The existing studies have dealt extensively with energy-aware scheduling mostly in hybrid flow shops [6] or batch systems [7], leaving a gap in the integration of environmental objectives in green flexible job-shop problems (GFJSP) and the management of material and energy flows. However, the need for sustainable logistics and integrated flow management is becoming increasingly critical due to regulatory pressure and market expectations.

From a practical viewpoint, total flow time is a key determinant of production efficiency and responsiveness, while carbon emissions are a major environmental cost. To the best of the authors' knowledge, this study is among the first to simultaneously address the minimization of total flow time and carbon emissions in a GFJSP setting, using both exact and metaheuristic approaches, contributing both scientifically, by introducing a novel bi-objective formulation incorporating machine-dependent emission rates and energy consumption, and practically, by offering insights into the

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management of multiple flows in GFJSP. In this paper, a Constraint Programming (CP) was developed for solving small instances, and a Particle Swarm Optimization (PSO) metaheuristic was used to solve medium and large-scale instances very efficiently. In this respect, the study presents a novel issue in sustainable scheduling by addressing both productivity and environmental performance in flexible production systems.

The remainder of the paper is structured as follows. Section 2 provides a review of the most relevant literature. Section 3 describes the problem under consideration. Section 4 presents an exact CP model and a metaheuristic PSO designed to handle large-scale instances. Section 5 presents the experimental results evaluations, ANOVA analysis, and discussion of results. Finally, Section 6 concludes the paper by summarizing the key contributions and outlining possible directions for future research.

2   Literature review

This review presents the contributions made since 2015, to reflect the recent developments in the FJSP mainly in terms of carbon emissions and total flow time minimization. This period shows an increasing interest of the research community towards integrating sustainability concerns, particularly energy consumption and environmental impact, into some of the classical scheduling objectives, such as makespan. This review examines the existing works based on their optimization criteria as well as solution methods. The next sub-sections discuss in detail methodologies aimed at carbon emission reduction and total flow time reduction in FJSP, referring to the state-of-the-art and how this helps identify research gaps.

2.1 Carbon emission minimization in FJSP

New methods have been introduced in the recent literature on the integration of carbon emissions with traditional performance criteria. For instance, the model, proposed by [8], combines deep reinforcement learning with programming techniques to minimize machine emissions and the carbon footprint of idle time. In [9], authors introduced an improved metaheuristics NSGA-II that optimizes makespan, operating cost and carbon emissions simultaneously. Authors in [10] developed a two-objective genetic algorithm that minimizes job tardiness and carbon emission. More recently, Ref. [11] proposed a GFJSP model for CO2 emissions directly into a mixed-integer linear programming (MILP) model, along with automated guided vehicle (AGV) transport and consumable usage. These contributions show how important it is to incorporate environmental criteria, specifically carbon emissions, into scheduling models, beyond establishing thresholds in reliability and productivity. Table 1 summarizes key studies related to low-carbon in FJSP, along with their methods, objectives, and limitations.

Table 1 Summary of previous studies of low-carbon approaches in FJSP

Reference	Method	Objective fonction(s)	Gaps
[8]	Deep Reinforcement Learning	Emissions from both machines and idle states	Lacks granularity in the emission rate per machine
[9]	NSGA-II	Makespan, energy cost, and carbon emissions	Uses uniform emission factors across machines
[10]	Genetic Algorithm	Total carbon footprint and tardiness	Lacks machine-dependent emission modeling
[11]	MILP + Logistics modeling	Emissions from AGVs, coolant, lubricants; includes CO_2	Emissions are aggregated; no per-machine emission modeling
[12]	Whale Optimization Algorithm	Carbon emissions	Simplified emission modeling; no machine granularity
[13]	Memetic Algorithm	Makespan, carbon emissions, and worker costs	Uniform emission rates; no machine-specific differentiation
[14]	Deep Reinforcement Learning	Carbon emissions and idle-time emissions	No machine-specific emission coefficients
[15]	MILP + Heuristic	Makespan and emissions in an industrial case	Uses general/global emission coefficients
[16]	Multi-objective MILP under ToU	Minimizes cost, carbon emissions, and maximizes customer satisfaction under ToU pricing	Focus on electricity tariffs; limited integration of machine-specific emissions

2.2 Total flow time minimization in FJSP

In contrast to carbon emission objectives, minimizing flow time remains a classical but less extensively integrated goal in flexible job-shop scheduling, especially when combined with environmental criteria. Flow time, representing the total time jobs spend in the system from release to completion, is crucial for improving production efficiency and responsiveness. In previous studies, research has focused mostly on traditional criteria such as makespan, tardiness, or

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workload balance [17-28], while few papers have considered total flow time minimization in conjunction with sustainability goals. Most of the scheduling research on environmental impact has concentrated on hybrid flow shops or batch processing systems [6,7], leaving a notable gap in the FJSP context. Given the increasing industrial demand for low-carbon manufacturing, addressing total flow time minimization alongside carbon emission reduction in FJSP is both timely and relevant (Table 2).

Table 2 Review of flow-time oriented approaches in FJSP

Reference	Method	Objective function(s)
[17]	Tabu search + Genetic Algorithm	Makespan
[18]	Multi-agent chemical reaction optimization + Tabu search	Makespan
[19]	MILP, Tabu search	Makespan
[20]	Greedy heuristics	Makespan
[21]	Jaya algorithm	Makespan
[22]	Artificial Bee Colony algorithm	Total flow time
[23]	Hybrid genetic algorithm + tabu search	Total flow time
[24]	Particle Swarm Optimization	Makespan, total workload
[25]	NSGA-II	Makespan, maximum tardiness
[26]	Particle Swarm Optimization	Makespan
[27]	Hybrid Genetic Algorithm + Variable Neighborhood Search	Makespan, total workload
[28]	Constraint Programming	Makespan, maximum flow time, maximum tardiness

In response to the identified research gaps, this study introduces both an exact and a metaheuristic to solve the GFJSP, targeting the simultaneous minimization of total flow time and carbon emissions, a practically relevant problem and yet an underexplored combination of objectives to our knowledge. We highlight total flow time as a way to improve resource continuity and reduce work-in-progress inventory, which differs from most previous studies that mainly concentrate on makespan or tardiness. Our goal is to improve scalability and solution diversity for large-scale instances by creating a CP model and a PSO algorithm that integrates a novel energy-aware encoding scheme.

3   Problem description and model formulation
3.1   Problem description and assumptions

The GFJSP addressed in this paper involves scheduling a set of independent jobs on a set of heterogeneous machines while optimizing both total flow time and carbon emissions. Formally, let $J = \{J_1, J_2, J_3, \ldots, J_n\}$ be a set of n jobs to be processed on a set of m machines $M = \{M_1, M_2, M_3, \ldots, M_k\}$. Each job J_j consists of a specific sequence of n_j operations $\{O_{1j}, O_{2j}, O_{3j}, \ldots, On_{jj}\}$ which must respect precedence constraints. (The operation cannot start before the completion of its predecessor). Each operation O_{ij} (with $i = 1, 2, \ldots, n_j$) can be processed by one machine from a **subset** $M_{ij} \subseteq M$ of eligible machines. The processing time P_{ij}^k, energy consumption E_{ij}^k, and carbon emission rate C_k depend on the machine $M_k \in M_{ij}$ chosen. Once started, an operation must run to completion without interruption (**non-preemptive scheduling**), and each machine can process at most one operation at a time (**disjunctive constraint**). All jobs and machines are assumed to be available at time zero. There are no precedence constraints between operations of different jobs, but the internal order of operations within each job must be preserved (conjunctive constraint). The GFJSP is thus a two-level decision problem: assign each operation to a machine from its eligible set (routing decision), and sequence the operations on each machine (scheduling decision). To illustrate the problem setting, Table 3 presents a sample instance with 4 jobs, 3 machines, and 10 operations, including the processing times and energy consumption of each operation on each machine.

Table 3 Data of the 4×3 GFJS instance

Job	O_{ij}	Processing times (min) / Machines			Energy Consumption (kWh)		
		M1	*M2*	*M3*	*M1*	*M2*	*M3*
1	O_{11}	3	5	2	0.20	0.25	0.15
	O_{21}	4	3	1	0.30	0.20	0.10
	O_{31}	1	5	6	0.20	0.28	0.35
2	O_{12}	8	3	3	0.18	0.14	0.13
	$O_{2,2}$	2	3	7	0.31	0.24	0.42
	O_{32}	4	5	5	0.17	0.21	0.20
3	O_{13}	9	1	3	0.13	0.10	0.12
	O_{23}	2	4	5	0.26	0.30	0.33
4	O_{14}	5	9	5	0.19	0.27	0.21
	O_{24}	1	3	5	0.21	0.22	0.24

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Depending on the structure of machine eligibility [29]: If each operation O_{ij} can be executed on all machines ($M_{ij} = M$), the problem is referred to as a Total GFJSP. But if $M_{ij} \subset M$ for at least one operation, it becomes a Partial GFJSP, which is inherently more difficult to solve due to reduced flexibility. The illustrated example corresponds to a Total GFJSP, where each operation can be performed on any of the three machines.

3.2 Model formulation

To address the studied GFJSP we formulate the following bi-objective model. This formulation integrates machine-level energy consumption and emission factors in a detailed manner, allowing for a more realistic representation of scheduling decisions in carbon-sensitive environments. It distinguishes itself by explicitly considering job-level total flow time, which better captures the responsiveness of the production system, and linking it with machine-specific emission contributions through the assignment of operations. By explicitly incorporating machine-dependent emission rates, the energy-aware formulation builds upon previous work on low carbon scheduling [9,10,14]. The notations of sets, parameters, and decision variables are presented in Table 4.

Table 4 List and description of the notations used

Notation	Description
Sets	
$J = \{J_1, J_2, ..., J_n\}$	Set of jobs (*j*: index of jobs)
$M = \{M_1, M_2, ..., M_k\}$	Set of machines (indexed by *k*)
O_{ij}	Operation *i* of job *j* (with $i = 1, 2, …, n_j$)
Parameters	
P_{ij}^k	Processing time of operation O_{ij} on machine M_k
E_{ij}^k	Energy consumption of O_{ij} on machine M_k
F_k	Carbon emission factor of machine M_k (kg CO_2/kWh)
L	A sufficiently large positive number (used in sequencing constraints)
Decision Variables	
$x_{ij}^k \in \{0,1\}$	1 if operation O_{ij} is assigned to machine M_k; 0 otherwise
$S_{n_j j} \geq 0$	Start time of the last operation of job *j*
$C_{n_j,j} \geq 0$	Completion time of the last operation n_j of job *j*
$y_{ij,hz}^k \in \{0,1\}$	1 if O_{ij} is scheduled after O_{hz} on machine M_k; 0 otherwise

The studied problem is formulated as follows:

$$\min f_1 = \sum_{j=1}^{n} C_{n_j,j} \tag{1}$$

$$\min f_2 = \sum_{j=1}^{n}\sum_{i=1}^{n_j}\sum_{k=1}^{m} x_{ij}^k \cdot E_{ij}^k \cdot F_k \tag{2}$$

Subject to :

$$\sum_{k=1}^{m} x_{ij}^k = 1, \qquad \forall j \in J, \forall i \tag{3}$$

$$S_{i+1,j} \geq S_{ij} + \sum_{k=1}^{m} x_{ij}^k \cdot P_{ij}^k, \quad \forall j \in J, \forall i < last\ operation\ of\ j \tag{4}$$

$$S_{ij} \geq S_{hz} + P_{kz}^k - L \cdot (3 - y_{ij,hz}^k - x_{ij}^k - x_{hz}^k), \quad \forall i,j,h,z, i \neq h\ or\ j \neq z, \forall k \in M \tag{5}$$

$$S_{hz} \geq S_{ij} + P_{ij}^k - L \cdot (y_{ij,hz}^k + 2 - x_{ij}^k - x_{hz}^k), \quad \forall i,j,h,z, i \neq h\ or\ j \neq z, \forall k \in M \tag{6}$$

$$C_{n_j,j} \geq S_{n_j j} + \sum_{k=1}^{m} x_{n_j j}^k \cdot P_{n_j j}^k \quad \forall j \in J \tag{7}$$

$$x_{ij}^k \in \{0,1\}, \ y_{ij,hz}^k \in \{0,1\}, \ S_{ij} \geq 0, \ C_{n_j,j} \geq 0 \tag{8}$$

Objective (1) seeks to minimize the total flow time (f_1), which is defined as the sum of completion times of all jobs and reflects overall system responsiveness and throughput. Objective (2) minimizes total carbon emissions by summing,

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for each scheduled operation, the product of its energy consumption and the emission factor of the assigned machine. Constraint set (3) ensures that each operation is assigned to one machine to guarantee the feasibility of machine allocation. Constraint (4) specifies the sequential technological precedence constraints within each job: No operation should start before its predecessor is completed. Constraint sets (5) and (6) enforce the sequencing of operations assigned to the same machine to avoid overlapping (one operation starting when the previous one finishes). Constraint set (7) states that the end time of a job is the time that the last operation in that job completes. Finally, constraint set (8) states that both assignment and sequencing variables should be binary, while start and finish times are non-negative.

4   Methods
4.1   Constraint programming model
We formulate the GFJSP using a CP model that simultaneously minimizes the total flow time and controls the total carbon emissions associated with machine usage. This model is especially suitable for combinatorial scheduling problems due to its expressiveness in modeling and its ability to represent sequencing and resource allocation constraints without linearization. According to [30], the CP is composed of three core elements: a set of decision variables, the domains of possible values associated with each variable, and a set of constraints. In scheduling, two key variable types are interval variables and sequences. An interval is defined by a process time, a start time, and an end time. A sequence is a collection of non-overlapping intervals assigned to the same resource. The following notations are defined in this model:

- $O[j, o, k]$: interval of operation o of job j on machine k with size duration $dur[j][o][k]$.
- S_k: sequence of operation scheduled on machine k;
- $endOf(O[j, o_{last}, k])$: Completion time of job j, defined as the end of its last scheduled operation.

The CP model formulation is expressed as follows:

$$min\left(w_1 \cdot \sum_{j \in J} max_{k \in M}\, endOf(O[j, o_{last}, k]) \right)$$

$$+ \left(w_2 \cdot \sum_{j \in J} \sum_{o \in O_j} \sum_{k \in M} PresenceOf(O[j, o, k]) \cdot energy[j][o][k] \cdot emissionFactor[k] \right)$$

Under constraint

$$alternative(O[j,o], \{O[j,o,k] | \ k \ \in M\} \quad \forall j \in J, \forall o \in O_j \tag{9}$$
$$endBeforeStart\big(O[j,o,k_1], O[j, o+1, k_2]\big) \quad \forall j \in J, \forall o \in O_j \backslash \{o_{last}\}, \forall k_1, k_2 \in M \tag{10}$$
$$NoOverlap(S_k) \quad \forall \, k \ \in M \tag{11}$$
$$endOf(O[j, o_{last}, k]) \geq endOf(O[j, o, k]) \quad \forall j \in J, \forall o \in O_j, \forall k \ \in M \tag{12}$$

Using a weighted aggregation with weights w_1 and w_2, the objective function simultaneously minimizes the total flow time and total carbon emissions. The *alternative()* constraint (9) ensures that each operation is assigned to exactly one machine. By ensuring that each operation begins only after the completion of its immediate predecessor, the precedence constraint (10) ensures that the operations within the same job are processed in the proper order. The **NoOverlap** constraint (11) ensures that no two operations overlap on the same machine, thereby enforcing the unary resource constraint. Constraint (12) defines the **completion time of each job** as the latest end time among all operations of that job.

4.2   Particle swarm optimization
In addition to the development of a CP model, an innovative PSO metaheuristic was proposed to solve the studied GFJSP. This method was a stochastic and population-based optimization inspired by the social behavior observed in bird flocks or fish schools. The search space of this algorithm is considered to be d-dimensional, and each particle l in the swarm represents a potential solution, defined as a position vector $X = (x_{l1}, x_{l2}, \dots, x_{ld})$ and a velocity vector $V = (\vartheta_{l1}, \vartheta_{l2}, \dots, \vartheta_{ld})$.

- **Particle encoding**

To enhance solution diversity and embed energy-awareness into the optimization process, we propose a novel encoding strategy based on three continuous-valued vectors: Temporal Execution Priority Vector (TEPV), Machine Efficiency Preference Vector (MEPV), and Dispatchability Perturbation Vector (DPV). Each of size N, where N is the total number of operations in the GFJSP instance. This hybrid encoding is well-suited for PSO and explicitly captures time sensitivity, machine efficiency, and controlled randomness in scheduling decisions.

Each element in the TEPV is a real number in the range [0,1] representing the urgency of scheduling the corresponding operation. Operations are sorted in ascending order of their TEPV values to determine the scheduling sequence; lower

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values correspond to earlier execution priority. Unlike traditional priority encodings, TEPV can flexibly incorporate external scheduling constraints such as due dates, peak energy periods, or time-dependent carbon taxation, thereby increasing the realism and responsiveness of the scheduling process.

Additionally, the MEPV is a vector of real values in [0,1], each of which represents an operation. Based on a Machine Efficiency Index (MEI), it encodes the preference for assigning the operation to one of its eligible machines. A variety of component, such as processing time, energy consumption, and carbon emission factors, are combined in the MEI. The MEI (13) is defined as follows for each operation O_{ij} and eligible machine M_k:

$$MEI_{ij}^k = \alpha \cdot \frac{1}{P_{ij}^k} + \beta \cdot \frac{1}{E_{ij}^k} + \gamma \cdot \frac{1}{C_k} \qquad (13)$$

Where α, β, and γ are user-defined weights that reflect the decision-maker's preferences. The machines are ranked in descending order of their MEI values, and the MEPV value is proportionally mapped to this ranked list to determine the machine assignment.

A controlled perturbation mechanism is introduced into the decoding process by the DPV, a third real-valued vector in [0,1]. During decoding, it adds adaptive randomness by modulating both TEPV and MEPV. Particularly in subsequent iterations, this stochastic modulation helps diversify the search and avoids premature convergence. A higher DPV value corresponds to stronger deviation from the deterministic decoding path, thereby encouraging exploration of alternative yet still feasible schedules.

The TEPV–MEPV–DPV encoding scheme offers a compact yet powerful representation that integrates time sensitivity, energy efficiency, and decision flexibility. It encourages the creation of more environmentally friendly schedules by directly integrating energy and emission factors into machine selection. While the DPV vector adds controlled randomness that strengthens global search capabilities, its responsiveness is improved by its flexibility in response to external factors like dynamic energy pricing or emission constraints. All things considered, this hybrid encoding offers a strong basis for creating effective and environmentally conscious metaheuristic solutions to the GFJSP.

To demonstrate the effectiveness of the proposed particle representation, we make use of the simplified GFJSP instance previously introduced in Table 1, which involves 4 jobs and 3 machines. The total number of operations is 10, so each particle is encoded as three real-valued vectors of length 10:

Table 5 Proposed encoding scheme

Operation	$O_{1,1}$	$O_{2,1}$	$O_{3,1}$	$O_{1,2}$	$O_{2,2}$	$O_{3,2}$	$O_{1,3}$	$O_{2,3}$	$O_{1,4}$	$O_{2,4}$
Index	1	2	3	4	5	6	7	8	9	10
TEPV	0.35	0.88	0.12	0.60	0.45	0.21	0.75	0.33	0.50	0.15
MEPV	0.60	0.20	0.90	0.25	0.70	0.45	0.80	0.10	0.55	0.30
DPV	0.05	0.12	0.10	0.08	0.03	0.15	0.04	0.20	0.18	0.06

Let $\delta = 0.2$ be the perturbation parameter for decoding TEPV (Table 5).

- **Particle decoding**

To ensure feasibility and transform the encoded particle representation into a valid schedule, a decoding procedure is applied in three stages, corresponding to the three components of the proposed encoding scheme: Temporal Execution Priority Vector (TEPV), Machine Efficiency Preference Vector (MEPV), and Dispatchability Perturbation Vector (DPV). This procedure guarantees adherence to the routing and scheduling constraints of the GFJSP.

Step 1: Operation sequencing from TEPV and DPV

Operations are first sorted in ascending order of their TEPV values. To avoid strict determinism and encourage search diversification, each TEPV value is adjusted using its corresponding DPV component. The adjusted priority score is calculated as (14):

$$Priority_{index} = TEPV_{index} + \delta \cdot DPV_{index} \qquad (14)$$

Where $\delta \in [0,1]$ is a perturbation parameter controlling the influence of randomness. While accepting slight changes that may help in escaping local optima, this controlled noise preserves the overall order. The final scheduling sequence is determined by sorting operations based on these adjusted priority values. Using the illustrative example, the adjusted value softens the strict priority order by incorporating a small perturbation from the DPV, helping the algorithm to avoid deterministic traps. The adjusted $Priority_{index}$ values are (Table 6):

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Table 6 Adjusted Priority$_{index}$

Operation Index	1	2	3	4	5	6	7	8	9	10
Priority$_{index}$	0.36	0.904	0.14	0.616	0.456	0.24	0.758	0.37	0.536	0.162

The operations are then sorted in ascending order of their Priority values, resulting in the following scheduling sequence:

$[3,10,1,8,6,5,4,9,7,2] \Rightarrow [O_{3,1}, O_{2,4}, O_{1,1}, O_{2,3}, O_{3,2}, O_{2,2}, O_{1,2}, O_{1,4}, O_{1,3}, O_{2,1}]$

Step 2: Machine assignment (Based on MEPV):

For each operation, the MEPV value is used to select one of the eligible machines. Assuming full eligibility of all machines (M1, M2, M3) for this illustration, the selected machine is calculated using (15):

$$Machine_k = [MEPV_k \times 3] + 1 \qquad (15)$$

This yields the following machine assignments (Table 7):

Table 7 Machine assignment using MEPV decoding

	O$_{1,1}$	O$_{2,1}$	O$_{3,1}$	O$_{1,2}$	O$_{2,2}$	O$_{3,2}$	O$_{1,3}$	O$_{2,3}$	O$_{1,4}$	O$_{2,4}$
Eligible Machines	M1, M2, M3	M1, M2, M3	M1, M2, M3	M1, M2, M3	M1, M2, M3	M1, M2, M3	M2, M3	M1, M2, M3	M1, M2, M3	M1, M2, M3
MEPV	0.60	0.20	0.90	0.25	0.70	0.45	0.80	0.10	0.55	0.30
Assigned Machine	M2	M1	M3	M1	M3	M2	M3	M1	M2	M1

Step 3: Schedule construction with constraint enforcement

Based on the sequencing and machine assignment obtained from the previous steps, the final schedule is constructed by enforcing key problem constraints. Precedence constraints are satisfied by ensuring that each operation starts only after the completion of its predecessor within the same job. To guarantee non-overlapping operations, machine availability is tracked, and each operation is assigned to the earliest feasible time slot on its designated machine. If any constraint violations occur, such as incorrect operation ordering or resource conflicts, they are penalized through a dynamic penalty function integrated into the fitness evaluation, thereby steering the optimization process toward feasible and high-quality solutions. This decoding mechanism effectively transforms each continuous-valued particle into a discrete and feasible schedule, allowing the hybrid PSO to navigate the solution space of the GFJSP while incorporating energy efficiency and carbon emissions into considerations.

- **Population initialization using logistic map**

Instead of using only uniform random sampling, a chaotic logistic map is used to create the initial swarm of particles in order to guarantee diversity and viability right away. The pseudo-random numbers produced by this nonlinear map, which is defined as $l_{n+1} = r \cdot l_n \cdot (1 - l_n)$ with $r = 4$, improve population diversity and aid in escaping local optima. The logistic sequence is used to determine the values of the triplet of continuous vectors (TEPV, MEPV, and DPV) that are initialised for each particle. The steps outlined in Section 4.2 are followed during the decoding process. Energy-conscious criteria incorporated into the MEI impact machine assignments during initialization, biassing the population towards more environmentally friendly scheduling arrangements. This hybrid initialisation approach preserves practical feasibility while improving early exploration.

- **Fitness evaluation**

Each decoded particle corresponds to a complete and feasible schedule, which is evaluated using a multi-objective fitness function. Since classical PSO requires a scalar fitness value, a normalized weighted sum approach is adopted to aggregate the two objectives (16):

$$Fitness_l = w_1 \cdot \frac{FT_l}{FT_{ref}} + w_2 \cdot \frac{CE_l}{CE_{ref}} \qquad (16)$$

Where FT_l and CE_l are the total flow time and carbon emissions of particle l, FT_{ref} and CE_{ref} are reference values, typically obtained from an initial heuristic solution. These reference values are computed once at the beginning of the optimization process and remain constant throughout all iterations, to ensure consistency and fairness in the evaluation of particles. The weights w_1, w_2 are user-defined and belong to the interval $[0, 1]$, with the constraint $w_1 + w_2 = 1$. They

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reflect the decision-maker's priorities between productivity and sustainability. By adjusting these weights, different trade-offs between the two objectives can be explored.

- **Velocity and position update**

The standard PSO update equations are adapted to handle the continuous encoding of the TEPV–MEPV–DPV scheme. Each particle's velocity and position are updated using (17):

$$\vartheta_l^{t+1} = \omega \cdot \vartheta_l^t + c_1 \cdot r_1 \cdot (p_l^t - x_l^t) + c_2 \cdot r_2 \cdot (g^t - x_l^t)$$
$$x_l^{t+1} = x_l^t + \vartheta_l^{t+1}$$

(17)

Where:
- x_l^t, ϑ_l^t: current position and velocity of particle l at iteration t,
- p_l^t: best-known position of particle i,
- g^t: global best-known position,
- ω: inertia weight,
- c_1, c_2: cognitive and social learning factors,
- r_1, r_2: random numbers uniformly drawn from [0,1].

After each update, particle components (TEPV, MEPV, DPV) are clipped to remain within [0,1], ensuring compatibility with the decoding process. To improve exploration in the discrete domain, a sigmoid-based probability transformation is optionally applied to velocity values, influencing the likelihood of structural changes in scheduling decisions.

- **Stopping Criteria**

To guarantee computational effectiveness and solution quality, the PSO algorithm ends based on two conditions. First, if the maximum number of iterations (T_{max}), which stands for a predetermined exploration limit, is reached, the algorithm stops. Second, if there is no improvement in the global best fitness value over a series of iterations (T_{stall}), which indicates convergence stagnation, an early stopping mechanism is initiated. In order to avoid needless computational effort, this set of criteria makes sure that the search process ends either after enough investigation or when more iterations are unlikely to yield better answers.

5 Results and discussion

To evaluate the performance of the proposed methods, computational experiments were carried out on a computer with Intel i7, 16 GB RAM under a Windows XP environment. The PSO was implemented in the programming language C# and the CP model was implemented using the Cplex CP Optimizer solver. To evaluate the performance of the proposed methods on small-sized instances, a dataset comprising ten classes of ten randomly generated instances each was constructed. The number of jobs was selected from the set {4, 8, 10, 12, 15, 20, 50}, while the number of operations per job was randomly drawn from the range {2, ..., 10}. The number of available machines was chosen from {5, 7, 10, 15, 20}. Processing times were generated according to a uniform distribution over the interval [1, 100]. For medium- and large-scale instances, the benchmark dataset used is the well-known rdata collection proposed by [30]. In this dataset, the number of jobs varies between 6 and 20, the number of machines ranges from 5 to 15, the number of operations per job spans from 5 to 15, and the total number of operations across all jobs ranges from 36 to 300.

5.1 Parameter settings

The PSO parameters were carefully calibrated to ensure a good balance between exploration and exploitation of the search space. The swarm size was set to 100 particles, and the maximum number of iterations T_{max} was fixed at 1000 and T_{stall} at 20. The inertia weight ω was decreased linearly from 0.9 to 0.4 over the iterations to balance global and local search. The cognitive and social acceleration coefficients c_1 and c_2 were both set to 2. The multi-objective fitness function aggregated the two objectives using a normalized weighted sum, as described in Section 4.1, with weights $w_1 = 0.5$ and $w_2 = 0.5$. These reference values remain constant throughout the optimization process to maintain a consistent evaluation framework. The carbon emission factor F_k of the machines is 0.54 (kg CO_2 /kWh).

5.2 Exact resolution results

In order to evaluate the CP model, we generate 6 classes of 20 instances (*Cl1-Cl6*) with several combinations for the parameters $n \in \{6, 10, 15, 20\}$ and $m \in \{5, 6, 10\}$. The processing times are randomly generated using the uniform distribution over the interval [1, 100]. Table 8 summarizes the average, minimum, and maximum computation times in seconds over 20 generated instances for each class configuration. The time limit of 600s was imposed: any instance not solved within this limit was considered unsolvable. The results show that the CP model was very efficient and able to

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solve instances up to 100 operations, a significant size compared to problems handled by other exact solution approaches. The model reliably solves *Cl1–Cl3* (≤ 75 operations) in under 9 seconds, affirming its strength on small to medium problem sizes. For *Cl4*, the average CPU time of 15 s and a 100% solve rate indicate that job count, more than total operations, drives CP complexity. In *Cl5*, the problem density increases; although many instances finish quickly, complexity spikes produce outliers up to 55 s, giving a 92% solve rate. Finally, *Cl6* presents the highest complexity: average time is 38 s, but difficult cases require up to 120 s, so 14% of instances timed out, yielding an 86% success rate (Table 8).

Table 8 Resolution results for CP model

Class	Size $(n \times m, \sum n_j)$	CPU$_{Avg}$ (in s)	{Min, Max} Times (in s)	% Resolution
Cl1	(6×6, 36)	0.1	{0.03, 0.13}	100%
Cl2	(10×5, 50)	0.1	{0.06, 0.2}	100%
Cl3	(15×5, 75)	4	{1.2, 8.5}	100%
Cl4	(10×5, 100)	0.1	{5, 30}	100%
Cl5	(10×10, 100)	12	{3, 55}	92%
Cl6	(20×5, 100)	38	{10, 120}	86%

5.3 PSO evaluation results

Table 9 presents the performance results obtained by the implemented PSO algorithm. The second column indicates the size of each class of the rdata benchmark, expressed as $(n \times m, \sum n_j)$. To evaluate the quality of the proposed metaheuristic, we compute the Relative Percentage Deviation (RPD) for each objective: total flow time (f_1) and total carbon emissions (f_2). For each instance, the PSO algorithm is executed 20 times. The best result among these runs is used as a reference to compute the RPD of that instance. At the class level (comprising 5 instances), the RPD is calculated as the average of the RPD values obtained for each instance within the class:

$$RPD_1^{Class} = \frac{1}{5}\sum_{I=1}^{5}[\frac{1}{20}\sum_r^{20}(\frac{f_{1,I}^r - f_{1,I}^{best}}{f_{1,I}^{best}}) \times 100]; \qquad RPD_2^{Class} = \frac{1}{5}\sum_{I=1}^{5}[\frac{1}{20}\sum_r^{20}(\frac{f_{2,I}^r - f_{2,I}^{best}}{f_{2,I}^{best}}) \times 100]$$

Where $f_{1,I}^r$ and $f_{2,I}^r$ are the total flow time and carbon emissions obtained at run r on instance I, and $f_{1,I}^{best}$ and $f_{2,I}^{best}$ are the best values obtained across 20 runs on instance I. To assess the robustness of the method, we also calculate the standard deviation of the relative deviations across the 5 instances in each class. These deviations are first computed per run as:

$$Dev_{1,I}^r = \left(\frac{f_{1,I}^r - f_{1,I}^{best}}{f_{1,I}^{best}}\right) \times 100; \qquad Dev_{2,I}^r = \left(\frac{f_{2,I}^r - f_{2,I}^{best}}{f_{2,I}^{best}}\right) \times 100$$

The standard deviation per benchmark class is then computed as the standard deviation of the average deviations per instance: $\sigma_1^{Class} = StdDev(\{\frac{1}{20}\sum_{r=1}^{20}Dev_{1,I}^r\}_{I=1}^{5})$ and $\sigma_2^{Class} = StdDev(\{\frac{1}{20}\sum_{r=1}^{20}Dev_{2,I}^r\}_{I=1}^{5})$. This evaluation provides insight into both the average performance and the consistency of the PSO algorithm across different instances and benchmark classes.

Table 9 PSO performance for GFJSP from rdata [30]

Benchmark Class	Size $(n \times m, \sum n_j)$	RPD_1 (%)	RPD_2 (%)	$StdDev_1$(%)	$StdDev_2$(%)	CPU$_{Avg}$ (in s)
la01-la05	(10×5, 50)	1.45	1.12	0.45	0.35	0.75
la06-la010	(15×5, 75)	3.05	2.34	0.85	0.60	3.82
la11-la15	(20×5, 100)	6.21	3.58	1.75	1.20	68.35
la16-la20	(10×10, 100)	5.38	4.80	1.30	1.10	95.58
la21-la25	(15×10, 150)	9.73	6.22	2.25	1.80	110.10
la26-la30	(20×10, 200)	12.05	7.66	2.80	2.15	175.05
la31-la35	(30×10, 300)	10.89	8.35	3.10	2.45	291.42
la36-la40	(15×15, 300)	13.12	8.70	3.45	2.70	336.15
Average		**7.73**	**5.35**	**1.99**	**1.55**	**135.15**

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The PSO performs effectively across medium- and large-sized instances. For the smallest classes (la01–la05), RPD_1 and RPD_2 remain low (1.45% and 1.12%, respectively) with minimal variability and negligible computation time (0.75 s), demonstrating efficiency and robustness. Moderately sized classes (la06–la15) maintain high solution quality (RPDs 3.05–6.21%) with low dispersion among runs. For larger instances (la26–la40), RPD values and variability increase moderately, reflecting the expected challenges in extensive search spaces, yet the algorithm remains competitive in solution quality and computation time (average 175–291 s). Overall, the PSO balances solution quality, stability, and computational efficiency, with average RPD_1 and RPD_2 of 7.73% and 5.35%, and standard deviations of 1.99% and 1.55%, confirming its suitability for solving GFJSP.

The ANOVA analysis was executed on RPD values across benchmark classes to determine whether mean differences were statistically significant, evaluating the method's stability and robustness to increased instance size and complexity. The results indicate a statistically significant difference between classes with *p-value < 0.05*. A closer examination of the box plots, represented in Figure 1, revealed a rather tight distribution for classes la01-la05 and la06-la10, indicating that variance among these classes is low, and the PSO algorithm can be assumed to be highly robust for small-sized problems. As the instance size increases, especially starting from class la31-la35, a trend is seen in both the median RPD and the interquartile range to increase, suggesting a subsequent drop in solution quality with an increase in variation. This being said, very few outliers across the entire set of classes lend credence to the conclusion of algorithm robustness. In conclusion, PSO performs well and is stable on small to medium-sized instances, with certain gradual degradation observed on larger problem sets.
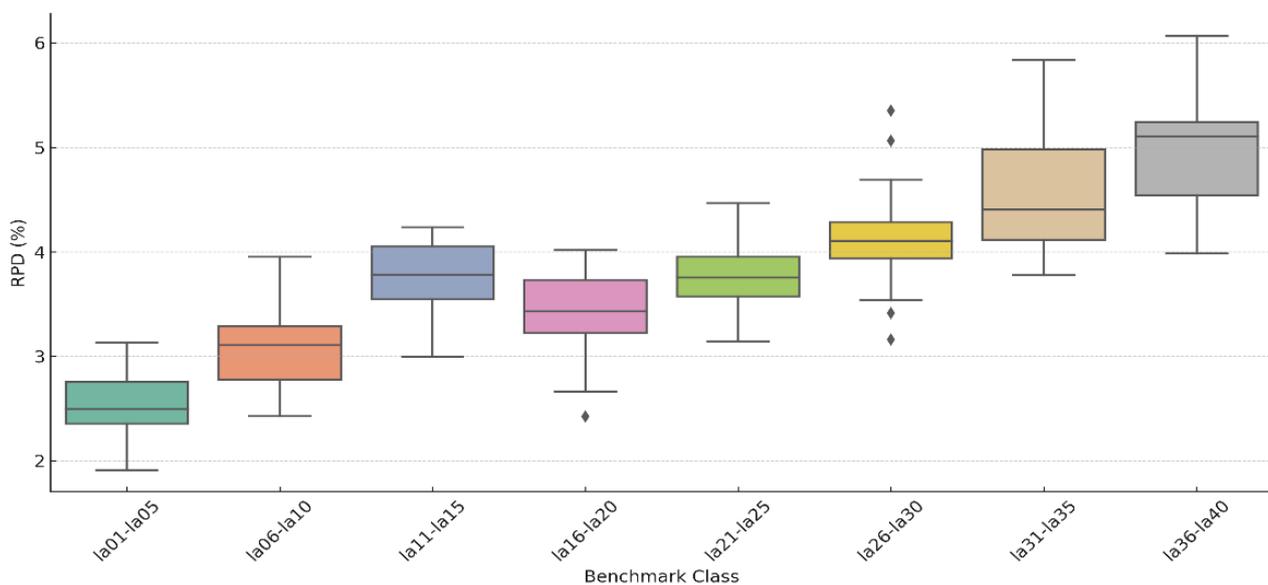
Figure 1 Box plots of RPD values across benchmark classes (20 runs per instance)

5.4   Discussion

The findings of this study highlight the relevance of proposing the two complementary methods, CP and PSO, enhanced with an energy-aware encoding scheme and population initialization via a logistic map, for addressing the GFJSP. Unlike traditional approaches that primarily aim to minimize makespan [3], results demonstrate that it is possible to simultaneously optimize both operational efficiency and sustainability criteria, particularly carbon emissions. This dual-objective perspective reflects a broader trend in industrial logistics research, where material, human, and energy flows are increasingly managed with sustainability considerations in mind. When benchmarked against existing heuristics and metaheuristics, the two proposed methods show competitive performance in reducing logistics and production flow while minimizing environmental impact. The sensitivity analysis and ANOVA tests further confirm the robustness of the PSO: changes in key algorithmic parameters lead to only minor variations in performance, while statistical analyses reveal that differences between solutions are significant. These results highlight both the stability and reliability of the proposed approach across small, medium, and large-scale problem instances.

Beyond numerical improvements, the model emphasizes the importance of simultaneously managing multiple flows, providing a more realistic representation of the complexity inherent in industrial logistics. From a managerial perspective, this approach offers a practical and structured tool to assess trade-offs between productivity and environmental responsibility. For example, minimizing waiting times while reducing energy consumption can directly translate into lower operational costs and enhanced compliance with sustainability regulations.

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Nevertheless, some limitations remain. Real-time disruptions and information flows are not modeled, and the experiments rely on benchmark datasets that may not capture all real-world variability. Future research could explore adaptive PSO strategies, stochastic disruptions, or integration with IoT and digital twin technologies to further improve responsiveness, robustness, and sustainability in dynamic, Industry 4.0 contexts.

Overall, the discussion emphasizes that these complementary methods not only contribute to academic knowledge but also offer practical guidance for industrial logistics managers seeking to align operational performance with environmental responsibility.

6   Conclusion and future research

This paper addressed the optimization of logistics and production flows in a green flexible job-shop environment, with the dual aim of enhancing operational efficiency (total flow time) and promoting sustainable performance (carbon emissions). Two complementary methods were developed: an exact CP model for small-sized instances, and a PSO algorithm enhanced with an energy-aware encoding scheme and population initialization via a logistic map for medium and large-scale problems. The results show that the proposed framework effectively reduces both total flow time and carbon emissions, demonstrating the value of combining exact and heuristic methods to tackle complex industrial logistics challenges. From a practical perspective, the methods improve material flow coordination, reduce waiting times, and promote more sustainable use of resources in flexible manufacturing systems. The CP model ensures optimal solutions for smaller instances, while the PSO algorithm produces high-quality solutions for larger instances within reasonable computation times. The sensitivity analysis confirmed the robustness of the PSO under varying parameter settings, further supporting the reliability of the proposed approach. This demonstrates how exact and metaheuristic methods can complement each other to address sustainable scheduling and flow management in industrial logistics.

Despite the promising results, some limitations remain, including the exclusion of information flows and real-time disruptions, which are increasingly relevant in Industry 4.0 contexts. Incorporating these aspects would increase the applicability of the scheduling models. Future research could explore multi-swarm or cooperative PSO strategies to improve convergence and solution quality in large-scale instances, and integrate stochastic disruptions to reflect dynamic production conditions. Additionally, combining PSO with machine learning models may enable predictive and adaptive scheduling, allowing the system to adjust in real time to production changes. The use of IoT-enabled data streams and digital twins could further enhance responsiveness, operational efficiency, and sustainability in modern flexible job-shop environments. Overall, this study provides both scientific insights and practical guidance for managing industrial logistics in a sustainable manner, offering a foundation for continued research in adaptive, data-driven, and environmentally conscious scheduling.

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The success factors and objectives of strategic monitoring practices in Sub-Saharan Africa: a case study of Moroccan exporting SMEs

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Abstract: The aim of this paper is to clarify the role of the strategic monitoring in the process of internationalization of the Moroccan SMEs in the Sub-Saharan African market and to identify the determinants and risks that influence the success or the failure of this internationalization. The objective is to assess a roadmap for the practice of strategic monitoring adapted to SMEs in the African context. By conducting a study on 14 Moroccan SMEs, the study's findings confirm that the strategic monitoring practices are influenced by the perceived uncertainties of internationalization relative to six environmental sectors. The management of uncertainty depends on the company's ability and its informational skills to access useful and valid information on the national and international markets. Managing the complexity of a constantly volatile environment requires strategic intelligence stimulated by strategic uncertainty. The results of analysing the collected information enable exporting SMEs to make the right strategic decisions and consequently reduce and/or eliminate perceived uncertainties.

1 Introduction

At the beginning of this third millennium, the African continent is emerging on a continental scale as a catalyst for foreign direct investment and a leading destination for SMEs. The African market's acuity illustrates the opportunities to which rival global players are rushing to explore as they seek to escape saturated markets.

As a result, the phenomenon of companies internationalizing toward Africa has intensified, leading to fierce competitiveness. Engaged in the global market, Moroccan SMEs face several challenges to seize and take advantage of the opportunities offered by this new emerging market. Global competitiveness requires these companies to focus on the search for relevant strategies and to take advantage of multilateral agreements maintained between their countries and those of the African continent. The trade openness, animated by these agreements, has been driven by the development of logistics at the continental level.

The management of uncertainty is therefore a critical challenge for any organization operating in the global market. To address the variable of uncertainty in this context, it must be addressed at the managerial level, taking into consideration the specific environmental conditions in which each organization operates and highlighting approaches designed to rationalize the management of uncertainty.

In this perspective, research into the mechanisms underlying the management of uncertainty in Africa takes center stage, revealing the determinants of strategic intelligence in the African continent and the practices adopted by the Moroccan SMEs exporters, contributing therefore to the monitoring of environmental sectors.

The aim of this paper is to clarify the role of the strategic monitoring in the process of internationalization of the Moroccan SMEs in the Sub-Saharan African market and to identify the determinants and risks that influence the success or the failure of this internationalization. In order to achieve this goal, we carry out a study involving 14 Moroccan SMEs targeting the sub-Saharan African markets. we selected the key determinants from the current state of the art in terms of strategic monitoring intelligence practices and identified the necessary skills required for implementing these practices.

2 Literature review

To frame the theoretical analysis of this problematic, we adopted an eclectic framework composed of three basic theories that qualify the role of information needed by the SME in the decision-making process. These theoretical

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contributions highlight the position of the manager in the decision-making process and the central role of the strategic monitoring.

2.1 *Organizational learning theory*

Organizational learning theory emphasizes the central role of the information. This theoretical approach posits information as an input that serve as a catalyst for organizational learning. The organizational learning is a driving force in the learning process.

McGill and al., (1992) [1] state that the international success of SMEs depends on their ability to learn and to react effectively to a multitude of changes. The initiation of this cognitive approach in the case of exporting SMEs has been attributed to Johanson and Wierdesheim (1975) [2] and Johanson and Vahlne (2017) [3]. Companies are confronted with uncertainties that require more caution and organizational learning to provide solutions.

Advocates of this approach (Johanson and Vahlne, 2017; Johanson and Wierdesheim, 1975; Eriksson and al., 1997) [2-4] recognize the role of information in reducing the psychological distance between home market and host markets during internationalization. This learning process aims to reduce psychological distance, which significantly influences the behavior of companies in their quest to internationalize. Psychological distance is defined as the sum of factors that impede the flow of information from and into the market [3].

In this context, the cognitive approach, initiated by [3], refers to the creation of objective knowledge acquired through the transmission of information [4]. The concept of market knowledge refers to information about markets and market operations that is stored and reasonably retrievable in the minds of individuals. [4] highlight two aspects of objective knowledge: business knowledge (customers, suppliers, competitors, etc.) and institutional knowledge.

Therefore, the company seeks anticipatory information that should be in line with its objectives (Argyris, 1982) [5]. Moreover, it is the processing of information that modifies the organization's potential behavior and, consequently, its learning (Huber, 1991) [6]. By information processing, [6] refers to its acquisition, exploitation, interpretation, and dissemination.

Several studies have confirmed the correlation between environmental uncertainty and the practice of strategic monitoring in different contexts (Zhang and al., 2012; Leaptrott and McDonald, 2015) [7,8] including the Moroccan context (Amine and Hicham, 2017) [9]. Based on the informational approach of learning theory, the authors' thesis suggests that an SME is more exposed to uncertainty as it scrutinizes the sources of change.

2.2 *Entrepreneurial theory*

Authors of the entrepreneurial approach, who focus on entrepreneurial organizations, share the view that the entrepreneur's ability to obtain and exploit information is decisive in explaining a company's innovative attitudes.

Hayek (1945) [10] was one of the first authors to identify the role of information in enlightening the entrepreneurial project. Hayek's contribution (1945) [10] demonstrated that the difficulties of adjusting to environmental volatility are particularly linked to the fragmented and contradictory dispersion of information. The information is conducive in optimizing resources. This assertion is further corroborated by Kirzner (2009) [11], who claims that the state of perfect knowledge among actors hardly reflects reality.

According to Hayek (1945) [10], economic theory must address essential issues to provide the actors, capable of ensuring optimal rationality, with informational resources. Entrepreneurs are given an advantage over other actors in terms of their ability and capacity to make better use of information.

However, the most appropriate formulation of the link between entrepreneurial activity and information refers to the theory of Kirzner (2009) [11] and Drucker (1985) [12]. Successful entrepreneurs tend to engage in organized and motivated exploration and analysis of sources of change that uncover new perspectives (Drucker, 1985) [12]. The entrepreneur must therefore control, or even master, the sources of change he considers to be sources of innovation, including political, regulatory, and competitive changes.

Kirzner (2009) [11] contends that the uneven dispersion of information, which creates asymmetry, contradicts the assumption of perfect knowledge among actors as proposed by the classical model, allowing the most vigilant/observant entrepreneur to succeed (entrepreneurial alert). Through his vigilance, the entrepreneur detects changes and consequently exploits the resulting opportunities not identified by others.

Supporting Kirzner's thesis, Busenitz (1997) [13] attests that the entrepreneur's behavior is manifested by their state of vigilance. Similarly, Kaish and Gilad (1991) [14] suggest that entrepreneurs analyze and exploit non-traditional sources of information, described by Granovetter (1973) [15] as weak networks. The informational process is attributed to strategic intelligence (Ganzert and al., 2012) [16].

In short, the perspectives drawn from studies that adhere to this approach affirm that the more an entrepreneur is vigilant, the more he monitors sources of change and possesses skills related to their sector of activity, allowing them to target sources of change (sources of information).

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2.3 Decision theory

Contributions that fall under the decision-making approach perceive the organization as an entity where decision-making is designed to be the organizational process through which problems are solved. The information constitutes an input in this process of decision-making. Problem management, arising from environmental change, is interpreted regarding the effectiveness and efficiency of decisions.

The contributions of Anderson (2007) [17] and Bendoly (2009) [18] serve as a significant foundation for comprehending decision theory from an informational perspective. Both authors were among the founders to highlight the advantages of strategic monitoring in the decision-making process. Furthermore, Anderson (2007) [17] indicates that decision-making is a process of incorporating these advantages (information). The effectiveness of those advantages/benefits depends on the relevance and reliability of the sources.

Decision-making is essentially a process of distinguishing, analyzing and choosing between alternatives Bendoly (2009) [18]. The purpose of this analysis is to identify the possible choices (in terms of information) and the possible factors (in terms of skills) that may affect the achievement of the desired objective. Problem-solving refers to the effectiveness and efficiency of the decision-making process.

However, several authors who belong to the same theoretical school - Augier and March (2008) [19], Morris and Ozawa (1979) [20], Bower (2017) [21] - indicates that certain organizations are able to adapt quite effectively, even if their use of information does not fully reflect the principles of efficiency.

Feldman and March (1981) [22] explain that the lack of clarity in this relationship is due to several factors. On the one hand, there are skill-related limitations: limited personal and organizational skills and limited analytical capabilities lead to a lack of perception of the validity of the information available to organizations. On the other hand, there is a propensity to collect and manipulate information for monitoring purposes instead of making decisions.

However, the critics of the above-mentioned authors do not deny the role of information as a tool in the decision-making process. The link between information and decision-making is more consolidated when the organization implements measurement instruments and possesses informational skills. These authors reveal the attributes of information, the skills of entrepreneurs, and the instruments required for effective management of the decision-making process.

By emphasizing the importance of entrepreneurship skills, Simon (2015) [23] argues that the key problem for entrepreneurs stems primarily from their ability to extract useful fractions of information, each of which conveys rich information. According to the author's guidelines, decision-making responsibilities must be allocated to each person who possesses the relevant information. Simon (2015) [23] stipulates that an entrepreneur is better informed when organizational mechanisms are established.

In summary, the contributions identified within the framework of decision-making theory suggest that an organization has access to rich information and has the ability to acquire and process this information (information skills).

3 Methodology
3.1 Methodological choice

We chose to conduct a qualitative abductive study, positioned within an interpretivist paradigm, as this study necessitates a significant level of contextualization. The perception of uncertainties arising from different sectors of the international environment (the determinant of intelligence monitoring) by different managers must be examined within the particular context of each exporting SME. Furthermore, the strategic monitoring systems employed by these companies are significantly influenced by the global context and the strategy they adopted.

Our purpose is to understand why and how Moroccan SME exporters practice strategic intelligence monitoring in sub-Saharan Africa. Additionally, we aim to identify the factors that contribute to its success, thereby enhancing the effectiveness of the strategic decision-making process in managing perceived export uncertainties.

This methodological approach aims to contextualize our study by considering the various perceptions of the actors involved (Roussel and Wacheux, 2005) [24], as the practice of monitoring and the identification of strategic issues to monitor are context-dependent. Thus, the roles assigned to directors and/or export managers, along with their experience and the interpretation of their situations, provide a deeper understanding of this phenomenon. Furthermore, the involvement of these diverse actors, considered as sources of information, enables an understanding of the logic and sectoral trend within the cases studied (Assabane and El Imrani, 2022) [25]. This corroborates the objectives of this research since it seeks to understand attitudes and perceptions. Consequently, we believe a qualitative study is essential and imperative, as it requires returning to theory to refine the variables.

3.2 Sampling

We seek to ensure that the sampling parameters used are in line with the predefined criteria: the saturation criterion for the number of cases, directors or at least export managers as interviewees, along with their export experience included.

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The sample size was limited once saturation was reached. A total of fourteen exporting SMEs targeting the sub-Saharan African market, selected from the industrial and agricultural sectors, fulfilled this first criterion. We also focused on the export directors and/or managers of these companies, regarded as experts in the sub-sectors selected in terms of exports and considering their experience in exporting to Africa.

For the second and third criteria, the practice of the intelligence monitoring in SMEs is a task assigned according to the literature to decision-makers, and its success is highly related to their information skills. Typically, decision-makers involve the most experienced manager(s) in the group in the decision-making process (Saunders, 2017) [26]. The managers' international experience acquired in terms of practice and extensive knowledge enhances their ability to offer high-quality advice to decision-makers.

Table 1 Characteristics of sampled SME exporters

Code	Sub-sector	City	Number of employees	Export experience to Africa		Countries of export in sub-Saharan Africa	Status interviewed
				company	Interviewee		
P1	Electromechanics	Tangier	14	20 years	14 years	North and West Africa (French-speaking Africa: 16 countries)	Export Director
P2	Food industry	Berrechid	395	18 years	11 years	Mauritania, Mali, Senegal, Burkina Faso, Benin, Niger, Gambia, Guinea Conakry, Equatorial Guinea and Bissau, Cameroon, Gabon, Congo, Togo, Chad, and Cabo Verde.	Export Director
P3	Textile	Tangier	150	8 years	20 years	Togo, Burkina, Mauritania, Guinee, Niger.	Owner Manager
P4	Chemical industry	Meknes	115	5 years	5 years	Mauritania, Senegal, Ivory Coast, Gabon, Burkina Faso.	Owner Manager
P5	Food industry	Casablanca	400	9 years	19 years	Angola, Cameroon, Congo, Ghana, Guinea, Ivory Coast, Gabon, Sierra Leone, Togo, Mauritania, Senegal, Burkina Faso, Cape Verde, Mali.	Export Director
P6	Food industry	Casablanca	35	6 years	10 years	Burkina Faso, Ghana, Ivory Coast, Benin, Togo, Kenya, Mali, Chad, Niger.	Owner Manager
P7	Food industry	Casablanca	250	19 years	12 years	Cameroon, Gambia, Guinea-Bissau, Niger, Senegal.	Export Director
P8	Agriculture	Marrakech	5	10 years	15 years	Senegal, Congo Kinshasa and Brazza-ville, Angola, Gabon, Burkina-Faso, Ghana, Togo, Benin, Ivory Coast.	Owner Manager
P9	Agriculture	Casablanca	9	10 years	14 years	Burkina-Faso, Benin, Ivory Coast, Senegal, Gabon, Ghana, Togo.	Owner Manager
P10	Agriculture	Agadir	10	6 years	7 years	Guinea Conakry, Benin.	Owner Manager
P11	Agriculture	Agadir	15	10 years	4 years	Senegal, Mali, Ivory Coast.	Export Director
P12	Agriculture	Agadir	25	15 years	15 years	ECOWAS (12 French-speaking countries), Senegal, Benin, Congo.	Owner Manager
P13	Agriculture	Agadir	+ de 200	18 years	8 years	West and Central Africa.	Export Director
P14	Agriculture	Taroudant	20	16 years	12 years	Ivory Coast, Gabon, Senegal.	Export Director

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4   Results and discussion

4.1   Data processing and analysis

After the triple coding, which allows us to generate new theme categories and enrich the analysis grid, we will proceed to calculate the frequency of themes in accordance with Guthrie's (2004) [27] guidelines. These guidelines state that the weight of a theme category increases with its frequency of occurrence. The occurrence table above serves as the basis of our summary report.

Table 2 Analysis by frequency of occurrence

Theme categories	Industrial sector							Agricultural sector							Cumulative frequency		
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	Absolute	Relative	Weight
1. Perceived export uncertainties	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes (3)	Yes	Yes	Yes			**14/14= 100%**
a. Market	1	0	0	0	0	1	0	2	1	0		0	0	0	5	1% (4)	4/14= 28.57%
b. Customers	4	3	0	2	3	3	2	4 (1)	0	2	0	2	2	2	30	6.03%	12/14= 85.71%
c. Competitors	0	2	2	1	1	2	2	2	2	0	1	0	2	2	20	4.02%	11/14= 78.57%
d. Policy	3	1	3	1	1	2	2	2	0	2	2	0	0	0	18	3.62%	10/14= 71.43%
e. Regulations	1	2	1	0	2	0	0	1	0	1	1	0	1	2	11	2.21%	8/14= 57.14%
f. Culture	2	3	2	1	0	2	1	3	1	0	0	1	0	0	16	3.21%	9/14= 64.28%
% Sub-theme inter-case	13.9	22.9	24.2	15.0	31.8	19.6	17.1	38.9 (2)	13.8	23.8	0 / 28.5	15.8	13.2	17.6	100	20.12%	
2. Strategic monitoring	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes			**14/14= 100%**
a. Frequency	11															11.47%	14/14= 100%
b. Mode	15	3	5	3	2	6	6	2	3	2	2	2	6	4	57	16.29%	14/14= 100%
% intra-case	32.9	12	5	6	4	7	5	3	5	2	2	3	7	5	81	27.76%	
	31.2	30.3	27.3	27.2	25.5	26.8		13.9	27.6	19.0	28.6	26.3	34.2	26.5	138		
3. Richness in reliable sources of information	Yes	Yes	Yes	Yes	No (5)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes		2.21%	**12/14=85.71%** / 7/14= 50%
a. Quantity	0	0	1	0	0	0	2	0	2	1	0	1	2	2	11	2.21%	6/14= 42.85%
b. Quality	1	3	0	2	0	0	0	2	1	0	0	0	2	0	11	7.24%	12/14= 85.71%
c. Reliability	5	3	2	3	0	3	4	1	4	2	0	2	4	3	36	11.67%	
% intra-case	7.6	12.5	09.1	15.0	00 %	5.9	14.6	8.3	24.1	14.3	00.0	15.8	21.0	14.7	58		
4. Richness in selective information	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		2.61%	**14/14=100%** / 8/14= 57.14%
a. Usefulness	1	2	1	2	0	0	0	2	0	2	1	0	0	2	13	3.82%	10/14= 71.43%
b. Quality	3	2	0	3	0	2	2	2	1	1	0	1	0	2	19	7.44%	14/14= 100%
c. Selectivity	5	4	2	2	2	4	5	1	2	1	1	2	3	3	37	13.88%	
% intra-case	11.4	16.7	9.1	21.0	9.1	11.7	17.1	13.9	10.3	19.0	14.3	15.8	7.9	20.6	69		
5. Information skills	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes			**14/14= 100%**
a. Techniques	14	0	1	2	2	6	5	1	1	1	1	1	2	2	39	7.85%	13/14= 92.85%
b. Relational	6	4	4	2	2	7	0	4	2	2	1	2	3	2	41	8.25%	13/14=92.85%
% intra-case	25.3	8.3	15.2	12.1	18.2	25.5	12.2	11.1	10.3	14.3	14.3	15.8	13.2	11.8	80	16.1%	
6. Uncertainty management	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes			**14/14= 100%**
a. Reduction	0	0	2	3	2	3	4	4	4	1	2	2	2	3	32	6.43%	12/14= 85.71%
b. Elimination	7	4	2	0	0	3	1	0	0	1	0	0	2	0	20	4.02%	7/14= 50%
% intra-case	8.9	8.3	12.1	9.1	9.1	11.8	12.2	13.9	13.8	14.3	14.3	10.5	10.5	8.8	52	10.46%	
Totals	79 100%	48 100%	33 100%	33 100%	21 100%	51 100%	41 100%	36 100%	29 100%	21 100%	14 100%	19 100%	38 100%	34 100%	497	100%	

(1): "4" means that this category was mentioned four times by the interviewee;

(2): 38.9% = (2 + 4 + 2 + 2 + 1 + 3) / 36;

(3): Yes = the category was mentioned at least once by the interviewee;

(4): 1% = 5 / 497

(5): No = the category was not discussed.

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In the cross-case analysis, all categories were significant except for cases 5 and 11, which omitted the category "richness of reliable information sources". Indeed, the subcategories " monitoring frequency" and "monitoring mode" emerged as the most prominent, representing total frequencies of 57 and 81, respectively.

For the horizontal analysis, when each category is considered individually and separately (entire), the perceived threats/risks are high for SMEs operating in the industrial sector, with at least 4 sources of uncertainty identified. This observation also applies to case 8, operating in the agricultural sector, where the manager possesses a higher level of export experience in Africa, spanning 15 years. The perceived uncertainties are linked to the lack of information on six environmental sectors due to the inaccessibility of local information sources. For instance, Moroccan companies that currently have access to these markets face challenges due to the lack of government aid for exports, thereby impeding access to anticipatory information. These uncertainties are mainly related to customer recovery, and linguistic and religious variations that exacerbate the cultural differences in destination countries. These differences, intensified by a lack of cultural sensitivity or misinterpretation of behavior, lead to the failure of the internationalization project.

Monitoring methods are both formal, relying on official documents for certain regulations, and informal, using partners in host countries. Nevertheless, companies mainly target non-formal sources, given their reliability, and prefer to monitor sources of change from the reality of the market field. For certain environments characterized by a predominance of state-controlled economies, the use of formal methods and state sources could provide these companies with information relevant to any political and regulatory changes.

Regarding the monitoring process and the validity of information, managers conduct a search (quantity) of information sources and evaluate their reliability and quality. Then, from the evaluated sources, they collect and process raw information, retaining the ones with the highest quality. The parameter of information selectivity, adopted by the interviewees, responds to the quality criterion. In addition to the quality of the information, managers conduct another processing step by comparing this information with the objectives they have designated. This selectivity allows them to retain only the useful information that satisfies their requirements.

Information selectivity is a process that persists throughout the monitoring phase, despite the reliability of the sources from which it is derived. In fact, the parameters required to select information remain independent of those of its sources. For sources, the quantity, quality, and reliability constitute the basis for respondents' choices. These subcategories linked to sources were mentioned 11, 11, and 36 times, respectively. As for information, it must be useful, of high quality, and selective. These criteria related to information were mentioned by 57.14%, 71.43%, and 100% of all respondents, respectively.

However, access to information sources and the processing of information requires information skills, mainly relational skills and business-related (technical) skills. These skills are considered by managers as stimulators of strategic intelligence monitoring because they facilitate access to reliable and high-quality sources.

Respondents agreed that information skills play a crucial role in accessing sources, evaluating the relevance of the resulting information, processing it, interpreting it, and using it. Nearly all interviewees, representing 92.85% of respondents, emphasized the active role of these skills in information behaviors. These skills, primarily related to professional and relational skills, must be reinforced through experience in exporting countries.

As for uncertainty management, managers are alerted to potential threats. They evaluate them and consequently act at the appropriate moment by making a strategic decision. The decisions and actions taken may be either defensive or offensive, depending on the nature of the threat encountered.

Uncertainty management represents the ultimate phase of elimination, mitigation, or reduction. This phase is associated with its nature and its inherent characteristics: political, regulatory, cultural, customer-related, or competitive. Indeed, respondents expressed divergent opinions regarding their decisions: 50% of cases advocated its elimination, while 85.71% of respondents recommended its reduction.

A combination of the two approaches is recommended in five cases in our sample, depending on the nature of the uncertainty: when information points to political non-stability, companies leave the country; if it's competition, they try to manage it. Through uncertainty management, the decision is to move forward or backward in the penetration of the market.

4.2   Discussion of results

Co-occurrence or contingency analysis refines our study by identifying co-frequency indices within the same segment of discourse and between different themes (Guthrie 2004) [27]. We performed relational coding in a contingency matrix, emphasizing the occurrence of two or more significant units in the same segment of discourse. As a result of this study, the contingency numbers allowed us to draw out insights by combining the relationships between the different themes identified in our thematic coding.

- The Determinants and Practices of Strategic Monitoring

According to the relational analysis, executives and/or export managers who perceive greater uncertainty in environmental sectors tend to practice strategic monitoring (for the agricultural sector) and intensify it (for the industrial

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sector) in these sectors, which are sources of change. The perceived uncertainties are due to a lack of information on the volatility of these sectors. Martinet A.'s (2010) [28] confirms this approach and attests that the company's environment should be defined by its actors, who are likely to exert a direct influence on this environment.

Based on the information source/uncertainty matrix (actor/theme), a particular monitoring method/mode is practiced or intensified for every sector that generates uncertainty. A variety of strategic monitoring methods had been developed, including political monitoring, competitor monitoring, customer monitoring, etc. To maintain efficiency, exporting SMEs focus on the source of uncertainty according to their information needs, thereby avoiding drowning in an abundance of useless information.

The monitoring method is dictated by the source of uncertainty and the company's ability to establish contacts. But the majority of targeted information sources are informal, considered by the company's actors to be the most reliable, and provide access to rich and valuable signals. In contrast, Formal sources of information, such as the media, the Internet, and reports, are of little importance since they only convey information that stakeholders would like to know.

Information extracted from formal sources should be compared with other sources to ensure its reliability (especially for policy-related and regulatory uncertainty). The reliability and veracity of such information need to be validated by fieldwork. Indeed, the existing literature regarding the characteristics of an information source highlights three attributes: reliability, quantity, and quality (Ivan and al., 2021) [29].

- Key factors for successful monitoring practice

Four findings are identified, highlighting the success factors associated with the practice of strategic monitoring: the manager's involvement in the information process, his relational skills (his ability to establish lasting contacts), his technical expertise (in terms of his business), and his export experience in Africa.

Through their involvement, managers play a decisive role in the strategic monitoring process; they frequently visit markets to collect and process information. They have three information-related roles: firstly, they are active observers of the flow of information concerning the development of international operations and external events affecting these operations (information on customers, competitors, suppliers, the political situation in a country, etc.). Secondly, they are disseminators of information within the company. Finally, they are the organization's representative to the external world.

Managers' relational skills facilitate access to reliable sources and the transfer of information. The sources are more accessible when managers have strong relational skills. Such skills enable them to develop their network of contacts, thereby enriching their sources of information. The reliability, quality, and quantity of these sources are the most important determinants for exporters.

Similarly, professional and technical skills give them the ability to select and interpret information by comparing information gathered from multiple sources. In the existing literature, misinterpretation of stakeholders' behavior leads to the failure of numerous internationalization projects (Ghemawat, 2008; Irrmann, 2010) [30,31].

The experience gained by export managers in Sub-Saharan Africa has provided them with solid business skills, primarily information processing skills, and has enabled them to develop a dense and lasting network of contacts. The literature accords information processing skills a moderating role in the context of exporting SMEs; it is export skills that significantly influence the ability of companies to analyze and exploit information appropriately.

Exporting SMEs are more informed about the volatility of their international environment when their managers are involved in the monitoring process and have solid information skills in their field. By employing both proactive and reactive intelligence monitoring and depending on the sector of activity, managers can access reliable and rich sources of information and also obtain selective, useful, and high-quality information.

- The aims of strategic monitoring

According to the interviewees, decision-making in the face of perceived uncertainties is not accidental; rather, it is an intelligent and deliberate action. Decision-making is a process through which the decision-makers extract the succinct fractions from the informational capital that provide valuable information about the threats they may encounter in the markets. Through this strategic information, uncertainties are analyzed and assessed according to their severity in relation to their uncertainty/information sources matrix.

In the literature, having sufficient information enables a detailed analysis of threats and opportunities (Tepeli and al., 2019) [32]. The more information an entrepreneur has about the international environment, the more likely he is to take risks (Tarek and al., 2019) [33].

Uncertainty management is a sequential process in the SMEs of the sample, which matures with the enrichment of information. The information gathered and processed during the strategic intelligence monitoring process is used as resources that SMEs utilize to strategically respond to threats. For this reason, the more advanced the intelligence process, the more mature the information resources of managers become, allowing them to reduce perceived uncertainties.

This informational capital is a toolbox to which managers refer for any rational decision. Uncertainty management is defined in terms of anticipation. Through this, certain threats must be avoided (such as those related to politics), while others must be reduced (such as those related to the market, competitors, and customers). However, the analysis of threats

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must consider their level of seriousness (criticality) and the opportunities that exporting SMEs can derive from environmental sectors. Consequently, exporting SMEs are less exposed to uncertainties if they have selective information from reliable sources.

5   Conclusion

Two sectors of activity in the Moroccan context are studied: the industrial sector and the agricultural sector, each of which has its particularities and specific characteristics. We, therefore, interviewed the managers of exporting SMEs or at least the export directors. The manager's export experience in sub-Saharan Africa is considered a determining factor as it enhances their "information skills."

The experience of the export directors and that of the companies are relatively high among SMEs in the industrial sector compared to those in the agricultural sector. This disparity is attributed to the nature of their activity.

Indeed, the practice of monitoring is relatively structured in the industrial sector, while it is intentional among managers in the agricultural sector. The responses of the managers in the agricultural sector show that the concept of "strategic monitoring" remains poorly understood, except in two cases where they simply refer to "the search for information" in their remarks. They are mainly concerned with uncertainties linked to customers and competitors.

Furthermore, the perception of uncertainty and the frequency of monitoring are quite high among industrial sector managers. They attach importance to all sources of uncertainty. The frequency of different categories of themes is relatively higher compared to the agricultural sector. These particularities are linked to the difference in managers' skills and management of information and the nature of their activity. The main themes mentioned (uncertainty, strategic monitoring, and uncertainty management) by managers in both sectors confirm these results.

The originality of this paper lies in its contribution to the development of a roadmap outlining the process through which Moroccan SMEs are gaining access to the African market by managing risks through the practice of strategic monitoring. Consequently, setting an example for SMEs of other countries with similar characteristics to those of the Moroccan economy.

However, the limitation of this study lies in the fact that "export experience" is too significant. It deserves to be classified in the analytical grid as the third subcategory of the "information skills" theme for higher representativeness. This suggests further perspectives regarding the conceptualization of a framework of information skills specific to Moroccan exporting SMEs.

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Simulation-based universal model for food SMEs: material flow optimization using Tecnomatix Plant Simulation

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Keywords: Tecnomatix Plant Simulation, discrete event simulation, production process optimization, food SMEs, lean manufacturing.
Abstract: Small and Medium Enterprises (SMEs) in the food and beverage sector face significant challenges in developing standardized production models that can be universally applied across different business scales and configurations. This study aims to develop a universal production model for grilled chicken rice SMEs using Tecnomatix Plant Simulation software to optimize workstation configuration and worker allocation. The research analyzed production data from 10 grilled chicken rice SMEs in Makassar City to establish baseline parameters for simulation modeling. Three workstation scenarios (4, 5, and 6 workstations) were simulated with varying worker allocation strategies: single worker per workstation, worker merge scenarios, and no-worker configurations to determine optimal resource utilization. The simulation results identified 4-workstation configuration with worker merge strategy as the optimal model, achieving 42.52% working time, 0.11% setup time, and theoretical maximum throughput of 295.89 units per day with 21:57 minutes average lifespan. The developed universal model includes standardized operating procedures and layout recommendations that can be adapted by various grilled chicken rice SMEs regardless of their current scale or configuration. This research contributes to simulation-based optimization methodology for small-scale food businesses and provides practical implementation guidelines for SME production standardization.

1   Introduction

Small and Medium Enterprises (SMEs) play a crucial role in Indonesia's economy, contributing more than 60% to the national Gross Domestic Product (GDP) and employing a significant share of the workforce [1]. Within this sector, the food and beverage (F&B) industry, particularly in major cities such as Makassar, has become one of the main pillars of the local economy. Among the most popular businesses, grilled chicken rice restaurants occupy a considerable market share and operate with diverse production scales and configurations.

A key challenge faced by F&B SMEs is the absence of standardized production models that can be universally applied across different scales and business settings. Most SMEs develop their own operational approaches based on available resources, which leads to significant variability in efficiency and productivity. This heterogeneity makes it difficult to define best practices and establish optimal strategies for resource allocation that could benefit the entire sector.

Preliminary observations conducted at 10 grilled chicken rice SMEs in Makassar City revealed substantial variations in operational configurations. The number of workstations ranged from 4 to 6, accompanied by different worker allocation strategies. Production capacity varied between 20 and 100 units per day, while cycle times ranged from 355 to 1725 seconds per unit. Worker arrangements also differed significantly, from single-person operations handling multiple tasks to more specialized multi-worker configurations.

This diversity reflects the adaptability of SMEs to local conditions and resource constraints, but it also highlights the lack of standardized models that could serve as references for both new and existing businesses. Developing a universal production model that can be adapted to different scales and operational configurations while ensuring efficiency is therefore crucial for advancing this sector.

Simulation-based modeling provides a promising approach to address this challenge. Tecnomatix Plant Simulation, developed by Siemens Digital Industries Software, is a discrete-event simulation platform designed for comprehensive modeling of manufacturing and production systems [2]. The software supports advanced capabilities in material flow simulation, resource optimization, bottleneck analysis, and performance evaluation through statistical measures. Version 2302.0003, which is used in this study, includes enhanced features for workstation configuration, worker allocation scenarios, and performance metrics analysis. These capabilities are particularly valuable for SMEs that operate with limited resources and cannot afford extensive trial-and-error experimentation.

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The strength of Tecnomatix Plant Simulation lies in its ability to model complex production scenarios with varying parameters such as process times, setup times, capacity constraints, and resource allocation. It also supports "what-if" analysis, allowing researchers to test alternative strategies before implementation. Its statistical functions further provide insights into performance indicators including working time percentages, throughput rates, average lifespans, and resource utilization.

This research aims to develop a universal production model for grilled chicken rice SMEs using Tecnomatix Plant Simulation version 2302.0003. The study focuses on identifying optimal workstation configurations and worker allocation strategies through systematic simulation analysis. Unlike traditional approaches centered on process flow, this research emphasizes the creation of adaptable operational models that can serve as templates for SMEs with varying scales and production settings.

2   Literature review

Research on production process modeling and optimization in food industry SMEs has demonstrated the effectiveness of lean manufacturing in improving operational performance and reducing waste [3]. Lean principles emphasize waste elimination, quality improvement, flexible production systems, and continuous improvement. Central to this philosophy is the classification of activities into three categories: value-adding (VA), non-value-adding (NVA), and necessary but non-value-adding (NNVA). Effective implementation requires systematic identification of these activities to maximize VA, eliminate NVA, and optimize NNVA [4].

Simulation tools have been increasingly applied to complement lean methods. Kopec et al. demonstrated how Tecnomatix Plant Simulation can identify bottlenecks and optimize material flow in manufacturing systems [5]. Pekarcikova et al. further showed its ability to streamline logistics flows with lean tools [6] and highlighted its effectiveness in bottleneck resolution using the kanban module, with simulation results differing from real operations by only 1.07% [7]. These studies confirm the reliability of Plant Simulation for production logistics optimization.

In the food sector, lean approaches have been applied across diverse contexts. Setiawan and Hernadewita reported a 21.4% reduction in production lead time through Value Stream Mapping (VSM), Kaizen, and layout redesign [8]. Valencia Vásquez et al. identified VSM, 5S, and Lean Six Sigma as the most commonly applied tools in food industries [9]. Musa and Alwan found that VSM plays the strongest role in enhancing sustainable performance [3]. Farissi et al. observed lean adoption in Moroccan food companies, where VSM, TPM, and 5S were common, while pull systems and kanban were underutilized [10]. In Sri Lanka, Silva and Warnapura reported positive correlations between lean practices and operational performance, with TPM strongly linked to quality improvement and cost reduction [11]. Mostafa and Ahmed demonstrated lean improvements in Egyptian food processing, achieving reductions in cycle and waiting times [12]. Ema et al. emphasized VSM and 5S as dominant drivers of waste reduction in food systems [13], while Veseli et al. showed that JIT, TPM, and SPC can significantly improve zero-waste implementation in SMEs [14]. Collectively, these studies highlight the consistent benefits of lean tools in improving efficiency and sustainability across food enterprises.

Recent developments also emphasize the integration of simulation into SME contexts. Trebuna et al. applied Tecnomatix Plant Simulation to digitalize VSM, demonstrating the added value of simulation in validating lean-based improvements [6,7]. Komkowski et al. investigated lean–Industry 4.0 integration, though their analysis focused on large enterprises rather than SMEs [15]. More broadly, international reviews show that discrete-event simulation is increasingly used in food SMEs to analyze layouts, resource allocation, and bottleneck mitigation. Simulation provides unique benefits where trial-and-error experimentation is costly or disruptive. Studies also stress the need to adapt simulation for low-automation, data-limited SME contexts. Case applications in food processing demonstrate that simulation supports throughput optimization, layout decisions, and investment planning, confirming its global relevance.

Despite these advances, a clear research gap remains. Most prior work has examined large-scale manufacturing, with limited focus on SMEs that operate with constrained resources and traditional processes. To date, no study has applied Tecnomatix Plant Simulation to develop a standardized operational model for grilled chicken rice SMEs. Furthermore, while lean and simulation have each been studied extensively, their integration into a universal model specifically tailored for food SMEs remains unexplored. Addressing this gap, the present study develops a universal model for grilled chicken rice production that combines lean principles with simulation, providing both academic and practical contributions to SME production logistics [16-18].

3   Methodology
3.1   Research framework

This research employs a simulation-based modeling approach to develop a universal production model for grilled chicken rice SMEs. The methodology focuses on systematic evaluation of different workstation configurations and worker allocation strategies using Tecnomatix Plant Simulation software version 2302.0003. The research framework integrates lean manufacturing principles with discrete event simulation to optimize production processes and develop an universal model for SME implementation.

The term 'universal' in this study refers to a standardized production model specifically tailored for grilled chicken rice SMEs in Makassar, which may serve as a reference for similar food SMEs in other Indonesian cities. However, its direct application to other food sectors requires further validation.

The conceptual framework follows an Input-Process-Output model where observational data from 10 SMEs (input) undergoes analysis through Value Stream Mapping, precedence analysis, and Tecnomatix Plant Simulation modeling (process) to generate a universal production model with optimized configurations and standard operating procedures (output) (Figure 1).
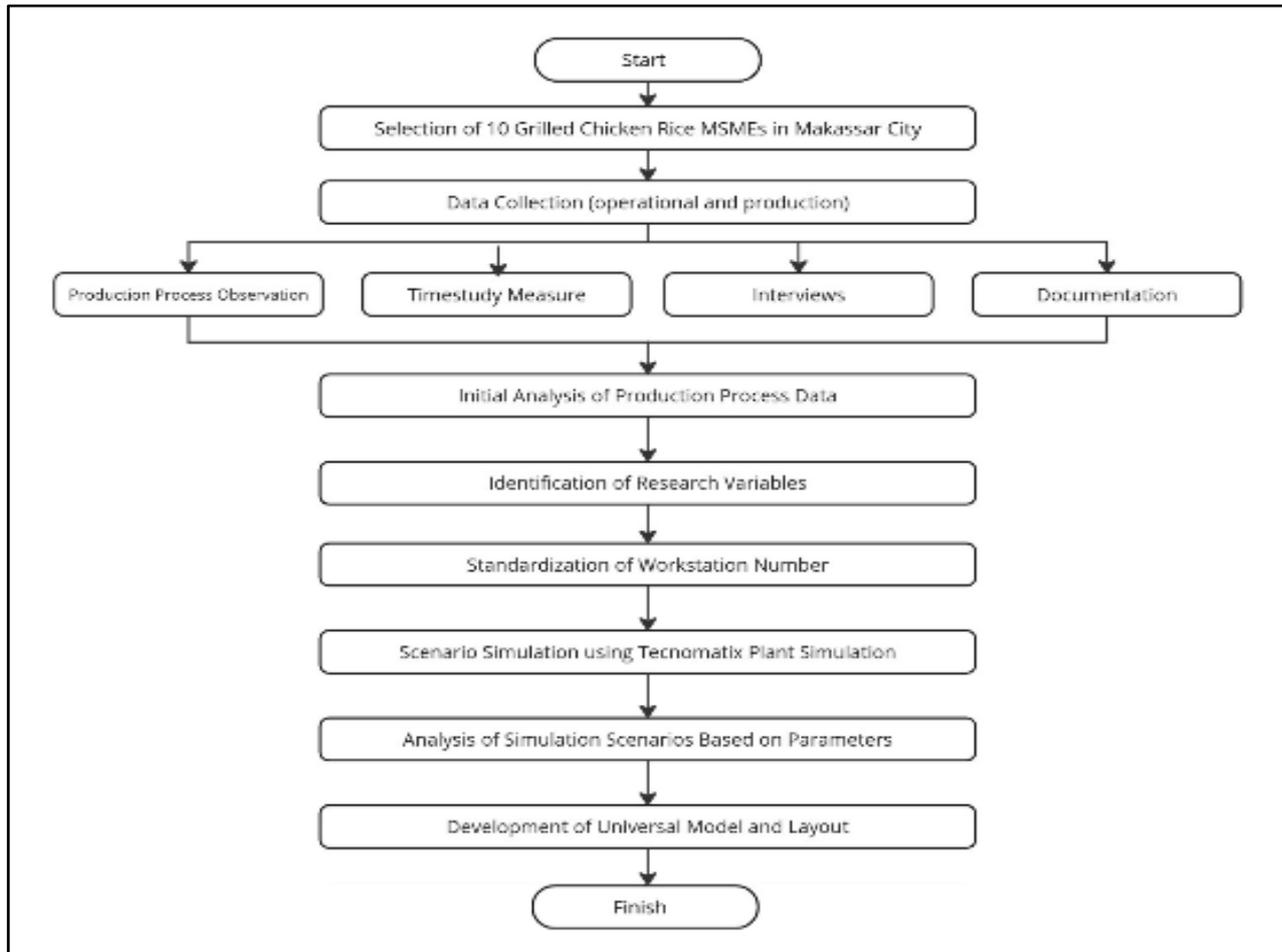
Figure 1 Research flow chart

3.2 *Research approach and sample selection*

This research uses a quantitative approach with a case study method. The case study was chosen to enable in-depth exploration of the production process at grilled chicken rice MSMEs in Makassar City. The research population is all grilled chicken rice MSMEs in Makassar City. The research sample consists of 10 grilled chicken rice MSMEs including: UMKM Bang Hasan Culinary, Kedai Mba Leny, Warung Makan Salsa, Warung Mas Sigit, Ikan & Ayam Bakar Pak Safar. Warung Khairul, Warung Mas Zidan Lamongan, Warung Ayam Krispi 58, RM Aroma Pangkep Perintis, and Sari Laut Barokah.

3.3 *Data collection and analysis*

Primary data was systematically collected from all 10 grilled chicken rice SMEs in Makassar City through a comprehensive multi-method approach designed to capture both quantitative operational metrics and qualitative process insights. The SMEs were strategically selected to represent the full spectrum of operational scales, configurations, and business models within the grilled chicken rice industry, ensuring robust data foundation for universal model development.

Primary data was collected from 10 grilled chicken rice SMEs in Makassar City through direct observation and time studies. The SMEs were selected to represent different operational scales and configurations:
1) Workstation Configuration Data

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- Workstation quantity and types
  Systematic categorization ranging from 4-6 workstations (WS) across different SMEs
- Core workstation identification:
  a) WS Grilling: Primary cooking process for chicken preparation
  b) WS Rice Preparation: Rice portioning and plating operations
  c) WS Side Dishes: Preparation of accompaniments (sambal, vegetables, soup)
  d) WS Serving: Final assembly and customer service
- Optional workstations
  WS Soup preparation and WS Frying (present in some SMEs)
- Workstation layout patterns
  Sequential, parallel, and hybrid arrangements
2) Process Time Data (cycle times for each workstation operation)
   - Detailed cycle time measurements:
     a) WS Grilling: 120-1500 seconds (highly variable based on cooking method and batch size)
     b) WS Rice: 15-90 seconds (depending on portion size and presentation requirements)
     c) WS Side Dishes: 15-90 seconds (varying by complexity of accompaniments)
     d) WS Serving: 15-30 seconds (final assembly and packaging)
   - Setup time documentation:
     Workstation preparation, cleaning, and material replenishment activities
   - Changeover times
     Transitions between different menu items or batch configurations
   - Peak vs. off-peak variations
     Performance differences during high and low demand periods
3) Production Capacity Data (daily output and operational hours)
   - Daily output capacity
     Ranging from 20 units (smaller operations) to 100 units (larger establishments)
   - Operational hours analysis:
     a) Shortest: 9 hours (Warung Mas Khairul, Mas Zidan Lamongan)
     b) Longest: 15 hours (Warung Makan Salsa, Sari Laut Barokah)
     c) Average: 12.15 hours across all SMEs
4) Layout Configuration Data (physical arrangement and material flow patterns)
   Layout type classification:
   - Sequential Layout: Linear flow from preparation to service (4 SMEs)
   - Separated Layout: Distributed workstations requiring worker movement (3 SMEs)
   - Centralized Layout: Hub-based arrangement with central coordination (3 SMEs)

3.4 Simulation model development

Using Tecnomatix Plant Simulation version 2302.0003, three primary simulation scenarios were developed:
1) Scenario 1: Workstation Configuration Analysis
   - 4 workstations: Grilling + Rice + Side Dishes + Serving
   - 5 workstations: Grilling + Rice + Side Dishes + Soup + Serving
   - 6 workstations: Grilling + Frying + Rice + Side Dishes + Soup + Serving
2) Scenario 2: Worker Allocation Strategies
   - Single Worker per Workstation (1WS/1Worker): Dedicated worker for each workstation
   - Worker Merge: Strategic combination of workstations under single worker control
   - No Worker Configuration: Pure workstation performance analysis
3) Scenario 3: Production Capacity Variations
   - Low capacity: 20 units adjustable
   - Medium capacity: 50 units adjustable
   - High capacity: 100 units adjustable

3.5 Simulation parameters

In the implementation of the simulation using Tecnomatix Plant Simulation, this study adopts key parameters configured based on field observation data collected from 10 grilled chicken rice MSMEs (Micro, Small, and Medium Enterprises) in Makassar City. These simulation parameters serve as the foundation for developing a universal model that is accurate and representative of the actual operational conditions of MSMEs. Key simulation parameters included:
1) Process Times

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Process times were established based on the average observational data gathered through direct field observations. Each workstation's process time was validated through repeated observations to ensure data consistency and accuracy. These process times encompass all value-added activities carried out at each workstation, from Grilling to Serving.

2) Setup Times

Setup times refer to the duration required to prepare and conduct changeovers between production processes. This includes equipment cleaning, raw material preparation, and workstation configuration prior to the start of production. Setup times are critical within the lean manufacturing context to identify potential waste and improvement opportunities.

3) Capacity Settings

Production capacity settings are designed to be adjustable, with flexible production targets (20, 50, and 100 units). This flexibility allows the simulation to accommodate various operational scales of MSMEs from micro to medium scale so that the resulting universal model can be adapted to the specific needs of each enterprise.

4) Working Hours

Standard working hours were set based on commonly observed operational hours among grilled chicken rice MSMEs. These operational hours vary between 8 to 15 hours per day, depending on the characteristics of each business.

5) Resource Constraints

Resource constraints include the availability of workers and the capabilities of each workstation, reflecting real-world MSME conditions. These parameters take into account the limited workforce (1–11 workers) and the multi-tasking practices commonly applied in small-scale operations.

3.6   *Performance metrics*

The simulation model was evaluated using Key Performance Indicators (KPIs) designed to assess the effectiveness and efficiency of the production process. These metrics were selected based on lean manufacturing principles and their relevance to MSME operations. The simulation models were evaluated using the following Key Performance Indicators (KPIs):

1) Working Time Percentage

Measures the proportion of productive time to total operational time. This indicator reflects workstation utilization and highlights opportunities to improve productivity.

2) Setup Time Percentage

Calculates the percentage of time spent on workstation setup relative to total operational time. This metric is important in identifying waste in lean manufacturing systems.

3) Waiting Time Percentage

Measures idle time and delays caused by production bottlenecks. This indicator is crucial for identifying areas within the process flow that require improvement.

4) Average Lifespan

Calculates the complete cycle time per product unit from start to finish. This metric serves as a key indicator of overall production efficiency.

5) Throughput per Day

Assesses the daily production capacity of the system. This indicator is essential for evaluating the system's ability to meet production targets.

6) Average Exit Interval

Calculates the time interval between completed product units. This metric provides insight into the consistency and continuity of the production process.

3.7   *Model optimization and validation*

Model optimization was conducted through a systematic process to ensure the validity and reliability of the simulation outcomes. The optimal model was determined through:

1) Comparative Analysis

A systematic comparison was conducted across all combinations of simulation scenarios (sequential vs. parallel flows, 4–6 workstations, varying production capacities) to identify the configuration with the best performance outcomes.

2) Performance Ranking

Performance-based ranking using KPIs was applied to determine the model with the highest effectiveness. Each scenario was evaluated using a weighted score across all established performance metrics.

3) Sensitivity Analysis

Robustness testing of the model was performed under various operational conditions. This analysis included variations in process times, demand fluctuations, and changes in resource capacity.

4) Validation

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Simulation results were compared with actual production data from the MSME case studies to ensure model accuracy. Validation focused on verifying cycle times, throughput levels, and bottleneck patterns observed in real operations.

4   Results and discussion

4.1   SME characteristics and configuration analysis

The analysis of 10 grilled chicken rice SMEs in Makassar City revealed diverse operational characteristics, as summarized in Table 1. The SMEs demonstrate significant variations in workstation configurations, worker allocations, and production capacities, providing a comprehensive baseline for universal model development.

Table 1 SME characteristics

No.	SME Name	Operating Hours	Workstations	Worker	Daily Capacity	Cycle Time (sec)
1	Bang Hasan Culinary	09.00 - 21.00	4	7	30 pcs	1160
2	Kedai Mba Lenny	06.30 - 18.00	5	1	40 pcs	375
3	Warung Makan Salsa	08.00 - 23.00	6	6	40 pcs	410
4	Warung Mas Sigit	16.00 - 02.00	4	3	100 pcs	455
5	Ayam Bakar Pak Safar	08.00 - 21.00	4	3	40 pcs	970
6	Warung Mas Khairul	17.00 - 02.00	4	2	20 pcs	850
7	Mas Zidan Lamongan	17.00 - 02.00	4	2	80 pcs	1235
8	Ayam Krispi 58	12.00 - 00.00	5	3	40 pcs	1725
9	Aroma Pangkep Perintis	10.30 - 22.30	4	11	40 pcs	1045
10	Sari Laut Barokah	11.00 - 02.00	5	4	20 pcs	355

4.2   Workstation configuration simulation results

Three workstation configurations were systematically evaluated using Tecnomatix Plant Simulation. The comparative analysis revealed significant performance differences across configurations, as presented in Table 2.

Table 2 Workstation parallel configuration analysis

No.	Parameter	4 WS	5 WS	6 WS
1	Working Time	63.31%	64.37%	59.86%
2	Setup Time	0,12%	0,13%	0.12%
3	Throughput per day	1708	1708	1704
4	Average Lifespan	04:28	04:39	5:29

The 4-workstation parallel (Figure 2) configuration demonstrated superior performance across all key metrics, achieving the highest working time percentage (63.31%) and lowest setup time (0.12%).
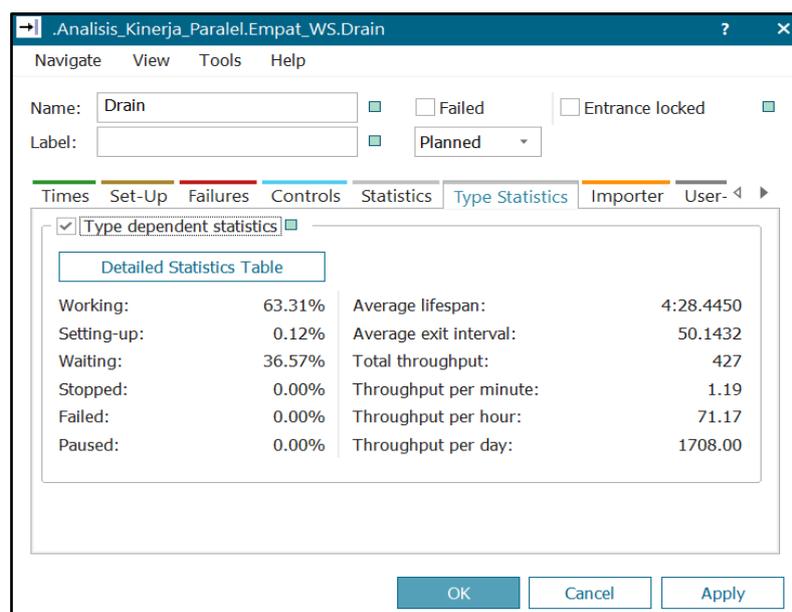

Figure 2 Output of 4 workstation parallel

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4.3 Simulation scenarios and process times

Simulations in determining the universal model were conducted by comparing sequential and parallel processes, using variations in process times including real time (empirical data from observations) and scenario time (target time for optimization). Tables 3 and 4 show the process times used in the simulation.

Scenario time data with a target of 10 minutes process time for all workstations was used to see the effectiveness of the model and workstations with certain time targets.

4.4 Simulation scenario analysis

To determine a universal model that can be effectively applied at the MSME scale, simulation scenarios were conducted by considering several aspects such as production capacity, production processes, and the number of workers. These scenarios aim to compare and analyze the optimal outcomes from each simulation scenario.

Table 3 Universal model process times based on average real times

No	Workstation	Data *Input Software* (in seconds)	
		Process Time	*Setup Time*
1	Grilling WS	702	60
2	Rice WS	54	30
3	Side Dish WS	51	30
4	Serving WS	23	20

Table 4 Universal model process times based on scenario times

No	Workstation	Data *Input Software* (in seconds)	
		Process Time	*Setup Time*
1	Grilling WS	420	30
2	Rice WS	60	30
3	Side Dish WS	60	30
4	Serving WS	60	30

The simulation framework was designed to evaluate three primary variables: production capacity (20, 50, and 100 units), operational timing conditions (real-time versus scenario-based), and workforce configurations (no worker, single workstation per worker, and worker merge configurations). This factorial design approach enables comprehensive analysis of system performance under varying operational conditions, providing insights into scalability and optimization potential for MSME applications.

The simulation parameters were established based on industry standards and preliminary system analysis, with each configuration tested under controlled conditions to ensure data reliability and comparative validity. The Tecnomatix Plant Simulation environment provided the necessary computational framework for modeling complex production interactions and generating statistically significant performance metrics.

4.4.1 Capacity-based and worker scenario analysis

This analytical framework systematically examines production performance across three capacity levels (20, 50, and 100 units), providing insights into scalability characteristics and resource optimization potential. The capacity-based approach enables identification of performance thresholds and efficiency patterns that are critical for MSME-scale implementation planning.

The analysis reveals distinct performance characteristics at each capacity level, with notable improvements in setup efficiency and resource utilization as capacity increases. This finding has significant implications for MSME investment decisions and production planning strategies, as it demonstrates the potential benefits of capacity expansion on overall system efficiency (Table 5).

Table 5 Production capacity analysis at 20 units (baseline configuration)

Parameter	Real Time			Scenario Time		
	No Worker	1WS/Worker	Worker Merge	No Worker	1WS/Worker	Worker Merge
Working Time (%)	52.47	52.47	43.05	45.85	45.85	42.91
Setting-up Time (%)	0.42	0.42	0.44	0.48	0.48	0.54
Waiting Time (%)	47.11	47.11	56.51	53.68	53.68	56.55
Average Lifespan (in minutes)	9:16	18:33	25:19	8:43	17:27	21:45
Average Interval Exit (in minutes)	3:57	7:54	7:51	2:26	4:52	4:39

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Throughput per hour (in unit)	7.64	7.64	7.64	12.24	12.24	12.24
Throughput per day (in unit)	183.39	183.39	183.39	293.88	293.88	293.88

The baseline configuration at 20-unit capacity establishes fundamental performance characteristics under minimal production constraints. Statistical analysis reveals significant performance differentials between operational modes, with real-time operations demonstrating higher working efficiency (52.47%) compared to scenario conditions (45.85%). However, scenario operations achieve substantially superior throughput performance, indicating a strategic trade-off between immediate efficiency and overall productivity. The worker merge configuration consistently exhibits reduced working time efficiency across both operational modes, suggesting inherent limitations in this approach at lower capacity levels (Table 6). This finding indicates that resource consolidation strategies may be less effective in constrained production environments, requiring careful consideration in MSME implementation planning.

Table 6 Production capacity analysis at 50 units (intermediate configuration)

Parameter	Real Time			Scenario Time		
	No Worker	1WS/Worker	Worker Merge	No Worker	1WS/Worker	Worker Merge
Working Time (%)	51.99	51.99	42.64	45.27	45.27	42.64
Setting-up Time (%)	0.17	0.17	0.17	0.19	0.19	0.21
Waiting Time (%)	47.84	47.84	57.18	54.55	54.55	57.14
Average Lifespan (in minutes)	9:21	18:43	25:33	8:50	17:40	21:53
Average Interval Exit (in minutes)	3:55	7:51	7:49	2:26	4:52	4:39
Throughput per hour (in unit)	7.67	7.67	7.67	12.30	12.30	12.30
Throughput per day (in unit)	184.01	184.01	184.01	295.08	295.08	295.08

The intermediate capacity configuration demonstrates improved system stability with reduced variability between operational modes. Statistical analysis indicates significant optimization in setup time efficiency (0.17% in real-time versus 0.42% at 20-unit capacity), representing a 59.5% improvement in setup efficiency. This finding suggests that moderate capacity increases yield disproportionate benefits in operational overhead reduction. The performance differential between real-time and scenario conditions remains consistent with baseline measurements, maintaining approximately 60% throughput advantage in scenario operations. This consistency indicates robust system behavior across capacity levels, supporting the viability of scenario-based optimization.

Table 7 Production capacity analysis at 100 units (optimized configuration)

Parameter	Real Time			Scenario Time		
	No Worker	1WS/Worker	Worker Merge	No Worker	1WS/Worker	Worker Merge
Working Time (%)	51.82	51.82	42.52	45.09	45.09	42.52
Setting-up Time (%)	0.08	0.08	0.09	0.09	0.09	0.11
Waiting Time (%)	48.10	48.10	57.39	54.82	54.82	57.37
Average Lifespan (in minutes)	9:23	18:47	25:38	8:52	17:44	21:57
Average Interval Exit (in minutes)	3:54	7:49	7:49	2:25	4:51	4:39
Throughput per hour (in unit)	7.67	7.67	7.67	12.33	12.33	12.33
Throughput per day (in unit)	184.16	184.16	184.16	295.89	295.89	295.89

The optimized capacity configuration demonstrates peak system efficiency within the tested parameters, characterized by minimal setup times (0.08–0.09% in real-time) and efficient resource utilization (Table 7). It achieves an 80.95% reduction in setup time compared to baseline conditions, indicating significant efficiency improvements at higher capacity levels. The alignment of worker merge performance with standard configurations at this capacity suggests that resource

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consolidation becomes more feasible as production scales. This insight is critical for MSME scaling strategies, implying that capacity expansion can support more flexible workforce management. The analysis shows that the parallel process with a production capacity of 100 units and worker merging at the Rice and Side Dish workstations yields optimal performance, with a daily throughput of 295.89 units, an average lifespan of 21:57 minutes, and a working time of 42.52 minutes.
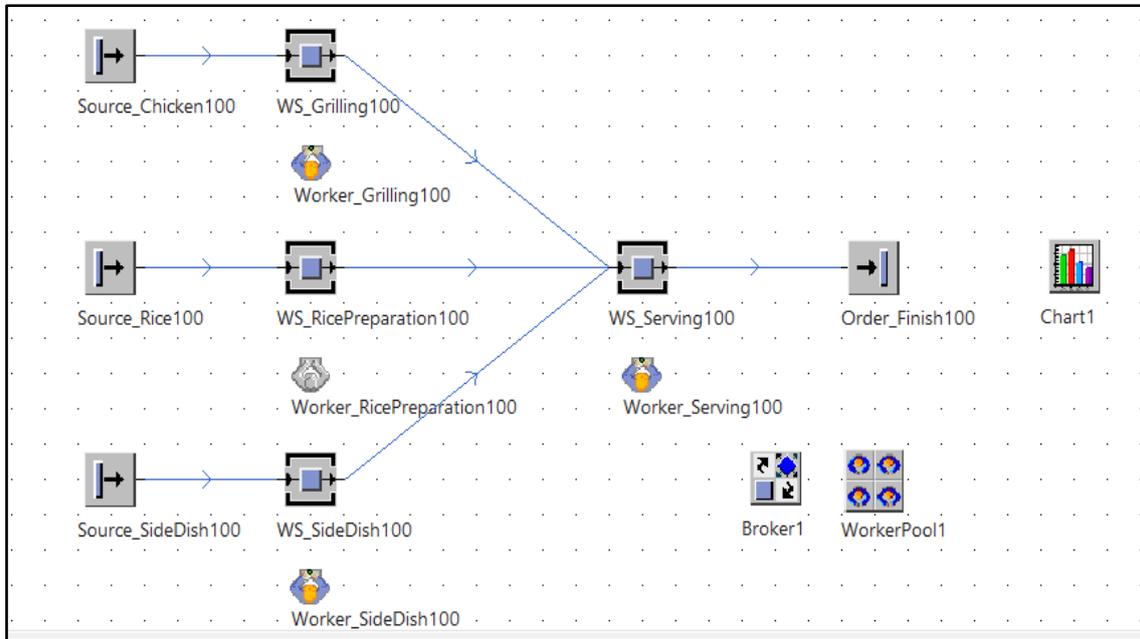
Figure 3 Universal model layout with 4 parallel workstations
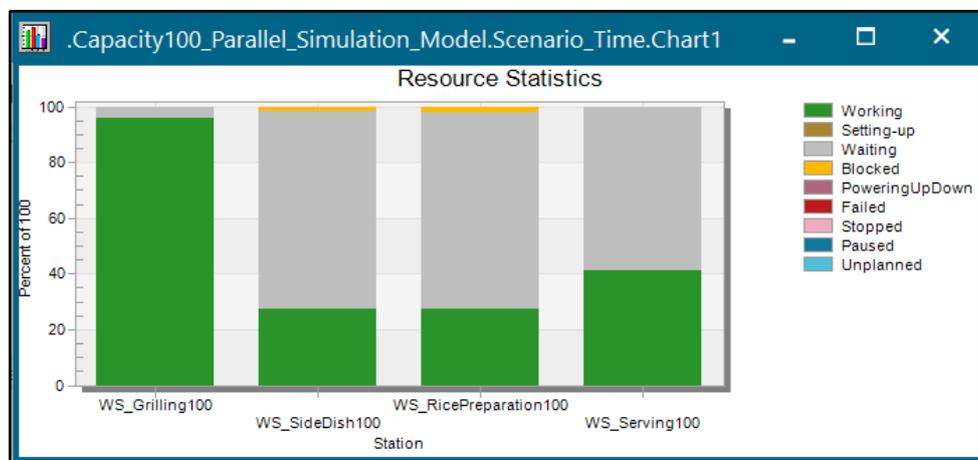
Figure 4 Universal model resource statistics graph

Analysis of the universal model layout with 4 parallel workstations (Figure 3) shows the production process flow of Grilled Chicken Rice consisting of grilling, rice, side dish, and serving workstations operating in parallel. Based on the Resource Statistics graph (Figure 4), it can be seen that WS_Grilling100 and WS_Serving100 have the highest working time percentages, indicating. optimal resource utilization levels. The Resource Statistics analysis confirms that WS_Serving100 recorded the highest working percentage (41.10%) with the lowest waiting time (58.90%), while WS_Grilling100 has a working time of 31.99% with a low blocked time (3.97%) WS_Serving100 and WS_RicePreparation100 have the same working time percentage (27.40%) but with differences in waiting time and blocked time, indicating differences in workflow efficiency between these workstations.

From Figure 4, it can be seen that the Universal Model Resource Statistics graph shows resource utilization across four different workstations. It can be observed that only three activity statuses occur in the production process: working time (green) indicating the workstation is actively producing, waiting time (gray) indicating the workstation is waiting for input, and a slight blocked time (yellow) indicating the process is slightly impeded. Other statuses such as setting-up,

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powering UpDown, failed, stopped, paused, and unplanned are not visible on the graph, meaning these conditions did not occur during the production simulation process.

4.5 *Statistical validation of the universal model*

After determining the optimal universal model configuration with four workstations and a worker merge strategy, further validation was required to ensure the robustness and reliability of the simulation results. While the initial analysis identified the 4-workstation parallel configuration as the most efficient, the strength of this conclusion depends on the statistical consistency of the simulation outputs. Therefore, detailed statistical results generated by Tecnomatix Plant Simulation were examined to provide variability measures, including mean values, standard deviations, and minimum–maximum ranges. These results not only confirm the feasibility of the selected universal model but also demonstrate its stability across different replications, thereby reinforcing its applicability for grilled chicken rice SMEs.

Order_Finish100	Life Time				Exit Time				Throughput		
	Mean Value	Standard Deviation	Minimum	Maximum	Mean Value	Standard Deviation	Minimum	Maximum	Total	Per Hour	Per Day
Part	21:57.0000	5:46.5072	9:00.0000	32:00.0000	4:39.9331	3:54.7210	2:00.0000	14:00.0000	300	12.328767	295.89041

Table 8 Universal model results statistics

Table 8 shows the detailed statistical results of the universal model. The average product life cycle (life time) was 21:57 minutes with a standard deviation of 5:46 minutes, ranging from 9 to 32 minutes. The average exit interval between completed products was 4:39 minutes (SD = 3:54 minutes), with a minimum of 2 minutes and a maximum of 14 minutes. The model produced a total throughput of 300 units per run, equivalent to 12.33 units per hour or approximately 295.89 units per day. These findings confirm that the universal model not only optimizes workstation configuration but also demonstrates stable and statistically reliable performance across replications.

These results are consistent with findings from international studies on SME food production, where discrete-event simulation has been shown to provide reliable performance benchmarks despite high process variability. The variation in product life cycle (9-32 minutes) reflects the inherent challenges of manual food preparation processes, including worker skill differences and grilling method variability, which are also reported in global SME contexts such as bakeries and catering services. The relatively stable throughput of 295.89 units per day highlights the robustness of the universal model, but it should be noted that this figure represents a theoretical maximum. In real-world applications, external factors such as demand fluctuations, raw material variability, and worker fatigue may reduce actual performance. Nevertheless, the statistical validation presented here not only reinforces the feasibility of the proposed universal model but also provides a rare contribution to the literature, as few studies have applied Tecnomatix Plant Simulation with detailed statistical rigor in traditional food SME contexts.

4.6 *Universal modeling with Tecnomatix Plant Simulation*

The research results show that 4 workstations (Grilling, Rice. Side Dish, and Serving) represent the optimal configuration for the grilled chicken rice production process. The use of Tecnomatix Plant Simulation in this research enables comprehensive modeling of the production process, including workstation analysis, material flow, and labor allocation. This software facilitates the development of a universal model that can be implemented by various MSMEs with minimal adjustment. The advantage of this modeling approach is its ability to simulate various scenarios without disrupting actual operations, providing valuable insights for data-based decision making. The research results show that the 4-workstation model with a parallel flow pattern is the optimal configuration for the grilled chicken rice production process. Although some MSMEs in the sample use 5-6 workstations, the simulation results confirm that adding workstations does not always improve efficiency and can add unnecessary complexity. The final universal model integrates all optimization and validation findings into a framework applicable across different MSMEs. The final universal model incorporates:
1) Optimal Workstation Configuration
   Simulation results determined that a configuration of 4 workstations is optimal, utilizing a parallel process flow for Grilling, Rice Preparation, and Side Dishes, and a sequential flow for the Serving workstation.
2) Recommended Worker Allocation
   An efficient resource allocation strategy was established through a worker-merging system at the rice and side dish workstations. This approach proved to deliver optimal efficiency without compromising output quality.
3) Standard Operating Procedures
   Detailed operational guidelines were developed for each workstation, including value-added activities, standard process times, and achievable output targets. These SOPs are designed to ensure consistency and quality in the production process.
4) Scalability Guidelines

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Adaptation instructions were provided for various MSME scales, from micro (20 units/day) to medium-scale operations (100+ units/day). These guidelines enable customization of the universal model according to the capacity and specific requirements of each enterprise.

5) Implementation Framework

A phased deployment plan was formulated to facilitate the adoption of the universal model by MSMEs. The framework includes stages of preparation, implementation, monitoring, and continuous improvement tailored to the operational characteristics of MSMEs in Indonesia. The universal model developed in this study not only offers a technical solution for optimizing production processes but also presents a practical roadmap for grilled chicken rice MSMEs to enhance operational efficiency through the application of lean manufacturing principles adapted to local contexts and resource limitations.

4.7 Flow line layout for the universal model

The flow line layout proposed in the universal model facilitates consistent material flow and reduces movement between workstations. This configuration optimizes the use of space and resources, while allowing process parallelization for workstations that are not interdependent. Layout visualization using Tecnomatix Plant Simulation facilitates communication and implementation of the model by MSME stakeholders. The visual representation helps identify relationships between workstations and clarifies process flow, which is important for adoption of the universal model by MSMEs with various backgrounds and levels of technical understanding.

4.8 Practical implementation of the universal model

Although the simulation results show potential for throughput improvement up to 295.89 units per day, it should be noted that this figure represents a theoretical capacity based on simulation with ideal conditions. Practical implementation of the universal model needs to consider real limitations faced by MSMEs, such as demand fluctuations, raw material quality variations, and space and labor constraints. MSMEs are advised to adopt the universal model gradually, starting with standardization of the 4 main workstations and implementation of the flow line layout. Process parallelization can be introduced progressively, starting with workstations that have minimal interaction. This gradual approach allows workers to adapt to changes and provides time for adjustments based on the specific conditions of each MSME.

Recent international reviews emphasize that while simulation provides strong theoretical guidance, its implementation in SMEs requires contextual adaptation due to resource limitations and variability in production environments. Yu and Zheng highlighted that SMEs often face significant challenges in applying factory simulation results directly, particularly because of constraints in data availability, low levels of automation, and limited managerial capabilities [19]. These findings reinforce the importance of adopting the universal model incrementally and tailoring it to the specific operational characteristics of each enterprise.

4.9 Limitations and further research

This research has several limitations that should be acknowledged. First, the simulation was conducted under the assumption that demand remains consistent and raw materials are always available, which may not accurately reflect the operational reality of MSMEs. Second, human factors such as worker fatigue and performance variability were not explicitly modeled in the simulation.

Future research could explore the integration of customer demand variability and inventory management into the model. As noted by Asmal et al. [20], inventory management plays a vital role in business operations and represents a crucial component of any company's operational framework. Additionally, exploration of alternative technologies for the grilling workstation presents a promising area for future investigation, given its identification as a potential bottleneck in the production process.

5   Conclusions

This study concludes that the universal model, developed through the integration of Tecnomatix Plant Simulation and lean manufacturing principles, provides a statistically validated framework for optimizing grilled chicken rice SMEs. Beyond demonstrating efficiency gains in throughput, workstation configuration, and resource allocation, the model offers practical implications for SME owners by serving as a benchmark for capacity planning, production standardization, and investment decisions without requiring costly trial-and-error experimentation.

However, practical challenges must be addressed in real-world implementation. Financial constraints may limit SMEs' ability to invest in additional resources, while the adoption of standardized operating procedures requires worker training and adaptation. Resistance to operational changes and variability in customer demand further complicate implementation, indicating that a phased and context-sensitive deployment strategy is essential for success.

From an academic perspective, this research makes a novel contribution by extending the application of Tecnomatix Plant Simulation to the context of food SMEs, an area that has been largely overlooked in existing literature dominated

by large-scale enterprises. The development of a universal model for grilled chicken rice production not only fills this research gap but also provides a replicable framework that can be adapted to other traditional food SMEs, supporting future efforts to advance production process standardization in resource-constrained environments.

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FinTech and digital platforms for financial inclusion in Jordan: logistics and operations aspects of sustainability

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Abstract: The study aims to analyze the role of financial technologies (FinTech) and digital platforms in expanding access to financial services in Jordan, taking into account the logistical and operational aspects of sustainable development. The goal of the work is to determine how innovative tools of mobile banking, digital wallets, crowdfunding and blockchain contribute to increasing financial inclusion, supporting small and medium enterprises and achieving sustainable development goals. The study assesses the impact of FinTech on the management of information and financial flows, identifies key barriers (technological, educational, regulatory) and formulates recommendations for improving the efficiency of the national financial sector. The methodological base includes a comprehensive analysis of quantitative indicators of the use of digital financial services and a qualitative assessment of the factors determining the readiness of the Jordanian financial system to implement FinTech solutions. This approach allows us to compare the level of digitalization of the financial sector with the possibilities of optimizing logistics and information flow management. The results show that FinTech tools expand access to finance for socially vulnerable groups, including rural communities and women entrepreneurs, stimulate entrepreneurial activity and strengthen market resilience. Prospects for further development are associated with improving public policy, creating intersectoral cooperation and developing digital competencies of the population. These measures will increase the competitiveness of the Jordanian financial system and accelerate its integration into the global digital economy.

1   Introduction

FinTech and digital platforms have become key to the modernization of the financial sector in recent years, especially in emerging economies. Jordan, in line with its strategic goals for sustainable development, is actively implementing innovative solutions to expand financial inclusion. The increasing digitalization of financial services is accompanied by the development of logistics and operational processes that ensure more efficient management of information and capital flows, speed up transactions and reduce costs. This is especially important for micro, small and medium enterprises, as well as for socially vulnerable groups, including rural communities and women entrepreneurs, who traditionally face barriers to accessing finance. The objective of this study is to analyze the role of FinTech solutions and digital platforms in expanding financial inclusion in Jordan, taking into account the logistics and operational aspects of sustainable development. To achieve this objective, the following research questions are put forward: 1) What factors determine the effectiveness of the implementation of FinTech tools in the Jordanian financial system? 2) To what extent do logistics and operational processes affect the availability of digital financial services for different categories of users? 3) What measures can help reduce barriers (technological, regulatory, educational) and strengthen intersectoral interaction? As a working hypothesis, it is assumed that the integration of FinTech tools (mobile banking, digital wallets, crowdfunding,

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blockchain) in combination with the optimization of logistics and operational processes can significantly increase financial inclusion and the sustainability of the national market. The methodological basis of the study is based on a combination of quantitative and qualitative analysis. On the one hand, statistical data on the distribution of digital financial services, usage rates and access barriers are used; on the other hand, expert interviews, content analysis of the regulatory framework and comparative analysis of international experience. This approach allows us to assess the readiness of the Jordanian financial system to implement innovative solutions and identify bottlenecks in logistics and information flow management. A comprehensive examination of these aspects will not only describe the current state of Jordan's digital financial ecosystem, but also formulate recommendations for government agencies, financial institutions and businesses to improve infrastructure, increase the financial literacy of the population and enhance the competitiveness of the national financial sector in the context of global digital transformation.

1.1 Theoretical aspects of FinTech and digital platforms for financial inclusion in Jordan: logistics and operations development

Financial technology (FinTech) is a set of innovative solutions that integrate digital tools into the traditional financial sector. Over the past two decades, this segment has evolved from a narrow niche into a global driver of transformation, spanning banking, payment systems, asset management, insurance, microfinance and crowdfunding. FinTech companies use mobile applications, distributed ledger technologies, artificial intelligence and cloud services to make financial services faster, more accessible and more transparent. In developed markets, they increase competition and reduce the cost of serving customers, and in developing countries, they promote financial inclusion by lowering barriers for low-income groups and micro and small enterprises. The impact of FinTech goes beyond payments and lending: it forms new business models, stimulates the creation of ecosystems around digital platforms, increases resilience to crises and expands data analytics capabilities for risk management. Given this global context, it is relevant to study how innovative financial technologies are being implemented in individual countries at different levels of development. Jordan, as an emerging economy, is using FinTech tools to expand access to finance and upgrade its logistics and operational infrastructure, making it an illustrative case study. Financial technology (FinTech) comprises a range of cutting-edge digital solutions that revolutionize traditional financial services, rendering them more accessible, efficient, and inclusive. The conceptual basis of FinTech is given in the ideas of digita l inclusion, innovation economy and the management of information in the banking industry [3]. In the proliferation of digital economy in Jordan, FinTech has emerged as an enabler to facilitate access of financial resources to especially underprivileged groups and MSMEs, thereby promoting sustainable economic growth [4]. A relevant theoretical framework for examining FinTech and financial inclusion is the digital inclusion model, which intends to circumvent traditional barriers through the adoption of mobile platforms, digital wallets, crowdfunding, and blockchain [5,6]. These solutions rationalize the logistics of information and finance, accelerate transactional process and makes it cheaper and safer [7, 8]. Logistics optimization is particularly relevant in a country such as Jordan, which suffers from infrastructure and digital disparities across different regions. Operational side of fin tech is the internal processes and business models in financial institutions with the ambitions to improve resilience, agility, and security [9]. This involves everything from automating operations and analytics and monitoring functions to handling threats from cyber and regulations risks. As per [10], operational innovation serves as the ground for sustainable growth of the finance sector in the digital transformation environment. In the Jordanian context, its adaptation of international theoretical models to the country circumstances and characteristics of the social structure, level of economic development, and the legal environment is an essential part of this [11,12]. Up to 2025 by the Vision 2025 Jordan Agenda, the vision highlights the importance of digitalizing the economy and enhancing financial inclusion requiring the holistic approach for FinTech development, including those components that related the modernization of logistics and operational systems [13]. A catalog of outstanding topics in the area of single-FinTech theory are regulatory issues, the guarantee of data security and the increase of digital literacy in the population, which is a prerequisite for the long-term sustainable use of technologies [14]. These issues are more pronounced in Jordan due to poor digital infrastructure in rural areas and lack of training for the workforce, both of which need specific educational and regulatory intervention. Recent literature suggests that the convergence of logistics and operational dimension facilitates the implementation of effective FinTech platforms. Fine-tuning information can be used to model adaptive and malleable financial systems that easily adapt to changes in the market and user needs [15]. Collaboration among government, private sector, and educational institutions is also essential to develop a digital ecosystem for financial inclusion and sustainable development [16]. Hence, a theoretical foundation of FinTech in Jordan is a combination of models of digital inclusion, logistics of information flow, and management of innovative activity. This, in turn, makes it possible to devise successful policies to promote financial inclusion and reinforce the country's economic resilience in the digital age.

1.2 *Conceptual features of implementation of FinTech and digital platforms in the financial and logistics industry: theories and views*

The World Financial technologies (FinTech) are taking part in the reformation of the financial sector and logistics domain. They offer new opportunities to increase the efficiency, safety and inclusiveness of financial and logistics services. Theoretical approaches to the development of FinTech and digital platforms There are some basic ones which take into account the influence of a nature of innovations for the organization of processes and interaction of its participants in the market. One of the fundamental principles is the image of digital inclusion, which leads to the idea of removing traditional barriers to the access to financial services promoted by modern technologies, such as the one finding in small entrepreneurs and the socially vulnerable [17]. In this sense, digital platforms are already intermediaries that bring together the different agents of the market, facilitating easy and rapid access to financial assets. Furthermore, digital business transformation theory also stresses that deep structure and process changes in existing organizations are required for the integration of new technologies [18]. Writers note that digital platforms not is only to change the procedures of providing services, but also formed the conditions that generate the emergence of new business models that contribute to business competitiveness. There are some logistical dimensions of implementing the FinTech such as management of the information and finance flow, which in practice require automation, data privacy and increased transparency [19]. Well streamlined information flow logistics help to cut operating costs and accelerate transaction processing, which is especially important given the complexities of nowadays supply chains or finance transactions that are closely interrelated. The working aspect of the implementation of FinTech is integrating the processes of the companies with the new digital instruments. These involve the automation of day-to-day activities, utilization of monitoring and analytics tools and cyber risk control [20,21]. The risk management concept in this domain refers to a combined method of technical, organizational and legal measures. In economics, a lot of attention is put on how digital platforms are changing financial inclusion and financial access [22,23]. This is true across both the financial and logistics industries where systems are being established that enable the collective work of customers, suppliers and regulatory bodies, maximizing efficiency and transparency. Success in FinTech implementation is also influenced by national regulatory characteristics and socio-economic aspects. [24], in emerging markets, the main hindrances relate to inadequate digital infrastructure, low digital literacy and legal constraints. These are the challenges that call for the adjustment of international theories to suit local situations. Contemporary scientific research acknowledges the necessity to develop an interdisciplinary approach to incorporate finance, logistics, information technology, and risk management [25]. This way a broad picture of the impact of several factors (on) and well-balanced strategies for a victorious digital transformation could be taken into consideration. In summary, the conceptual attributes of the implementation of FinTech and digital platforms in financial and logistics have its foundation on digital inclusion, business process, information flow and risk. Such a system would involve a convergence of technical, organizational and regulatory aspects tailored to the local market.

2 Methodology

2.1 *Peer review process*

This research will shed light on the potential positive effects of FinTech and digital platforms (DP) on enhancing financial inclusion growth in small-medium enterprises (SMEs) in Jordan concerning logistical and operational mechanisms that would lead to the economic development and sustainability of the country. In order to obtain a deep reflexional the research methodology is considered as mixed methods - quantitative and qualitative one allowing us to consider the problem from different sides and so to find deep relations and to propose practical recommendations. Hybrid methods (mixed methods) are very popular in the current scientific research, especially in the search for complex phenomena such as the digital transformation of the financial sector and its effect on the economy [25,26]. Quantitative methods provide objective numerical indicators that reflect the scale and dynamics of FinTech innovation, while qualitative methods help to understand the social, behavioral, and regulatory conditions in which these technologies are being implemented. In the context of Jordan, where the financial sector is rapidly developing but also faces a number of specific challenges (infrastructural, cultural, and institutional), the use of mixed methods allows us to form a more accurate and multifaceted picture of the processes than using only one of the approaches. The quantitative component of the study is based on secondary data obtained from key official sources. Based on these data, four key indicators of financial inclusion are examined:

- Digital financial inclusion for the population (Dcf) - measured by the share of the adult population actively using mobile and online banking services;
- Penetration of mobile accounts (Pmc) - reflects the percentage of mobile financial account users;
- Use of FinTech platforms by small and medium enterprises (Ufp) - the share of MSMEs using digital tools for financial management;
- Regional differences in accessibility (Rda) - an index reflecting the uneven distribution of digital financial services across the country's geographic regions.

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For quantitative analysis, a multiple linear regression model was built, which allows us to assess the impact of these factors on economic indicators of sustainable development. The formalization of the model is presented by the following formula (1):

$$Y_i = \beta_0 + \beta_1 + Dcf_i + \beta_2 + Pmc_j + \beta_3 + Ufp_i + \beta_4 + Rda_i + \varepsilon_i \tag{1}$$

Where Y_i is an economic indicator for region i (e.g., GDP per capita, employment rate, poverty reduction rate); β_0 is a model constant; $\beta_1, \beta_2, \beta_3, \beta_4$ are regression coefficients reflecting the influence of the corresponding financial variables; ϵ_i is the model error.

To ensure the reliability and validity of the results, a data triangulation method is used, which involves comparing and cross-analyzing information obtained from the quantitative and qualitative components of the study, as well as from case studies and the regulatory framework. This approach minimizes subjective distortions and increases the accuracy of interpretations [27]. For the quantitative section, a regression analysis has been selected as the most suitable instrument in order to determine the relationship between the advancements in digital financial services and economic variables. The multiple linear regression equation can be applied to quantify how much the important factors influence (2):

$$Y_i = \beta_0 + \sum_{k=1}^{4} \beta_k X_{k,i} + \epsilon_i \tag{2}$$

Where X k is a binary variable such as the availability of digital services and the use of FinTech platforms. Correlations also show the nature and degree of relationship, which is important to establish possible cause-and-effect relationship, and form hypothesis in in the qualitative research [28]. The choice of linear regression as the main method of data analysis is determined by a number of interrelated factors related to both the nature of the variables under study and the characteristics of the available data array. First of all, the key indicators included in the model have a quantitative measurement scale, which makes them suitable for assessing relationships using parametric methods. A preliminary analysis of the distribution of variables showed the absence of strong asymmetry and extreme outliers, which allowed us to consider the assumptions of normality of residuals and homoscedasticity to be sufficiently fulfilled. The second important aspect is the need to obtain an interpretable model that would allow not only to predict the values of the dependent variable, but also to quantitatively assess the influence of each factor. Linear regression provides a direct and transparent form of dependence, where the coefficients reflect the marginal impact of the independent variable at a fixed level of the others. This is especially important in the development of management recommendations, since it allows you to clearly identify the key drivers of change and compare them with practical solutions. Finally, the choice of linear regression was dictated by the availability of data. The sample size and observation structure provide sufficient statistical power for a robust estimation of coefficients with a relatively small number of predictors. In addition, the availability of historical data at regular time intervals allowed us to take into account possible trends and conduct a preliminary check for multicollinearity. The combination of these circumstances makes linear regression a methodologically justified tool that provides a balance between accuracy, simplicity, and interpretability, which is especially important in applied analysis and the preparation of recommendations based on empirical data.

3 Results and discussion

Financial inclusion in Jordan remains one of the key challenges to sustainable economic growth. According to World Bank reports, more than 60% of Jordan's adult population does not have full access to formal financial services. In this regard, FinTech solutions and digital platforms that can remove barriers, reduce transaction costs, and ensure inclusive access to financial products are becoming increasingly important [29]. In this context, FinTech and digital platforms play a critical role in reaching previously excluded segments of the population by reducing costs, increasing transparency, and speeding up transactions. Faced with the need to modernize its financial infrastructure and logistics processes, Jordan is relying on innovations ranging from mobile wallets to blockchain platforms. This part of the article presents the results of a study on the adoption of these technologies and their impact on the sustainable development of financial inclusion, especially in rural and marginalized areas. Key aspects of the digital transformation of the financial sector of Jordan are presented in Figure 1.

Conceptual aspects and directions of development of financial inclusion in Jordan: logistical and operational aspects are presented in Figure 2.

Sustainable development focuses not only on economic efficiency but also on social inclusion. FinTech can reduce gender and regional inequalities in access to finance. In addition, digital platforms, based on APIs and open standards, contribute to the formation of ecosystems that include banks, NGOs, startups and government. FinTech and digital platforms in Jordan play a vital role in increasing sustainable financial inclusion. The technologies used - from mobile

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wallets to blockchain platforms - not only ensure operational efficiency, but also solve key social problems: expand access to finance, minimize costs, and increase transparency. The role of the state in shaping the regulatory environment and supporting logistics infrastructure is also critical. The trend towards integrating FinTech into related industries (logistics, agriculture, healthcare) will increase, making digital platforms a central element of sustainable development.

The analysis of secondary data included descriptive statistics for statistical interpretation. Research data showed mobile wallet adoption in Jordan had penetrated to 32% by 2023 and mobile financial services engaged 2 million country users. FinTech startup numbers in Jordan experienced an 8% yearly increase from 2015 to 2023 which resulted in 58 active companies during 2023. The study results demonstrated that urban locations exceeded rural areas in mobile wallet usage through their higher adoption percentage of 38% as against 24%. As figure 3 Mobile payment transaction volumes rose by 15% every year during the past five years because FinTech services started to become deeply integrated into daily life. Structuring FinTech and Digital Platforms in Jordan: Logistics and Operations Aspects of Sustainable Development are presented in Table 1.
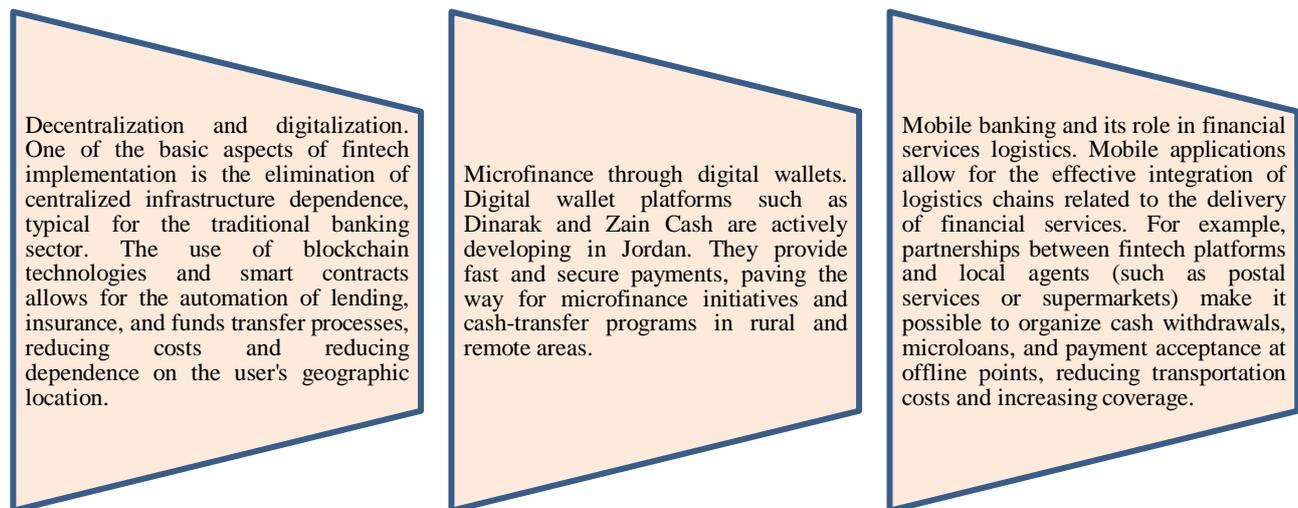
Figure 1 Key aspects of the digital transformation of the financial sector of Jordan
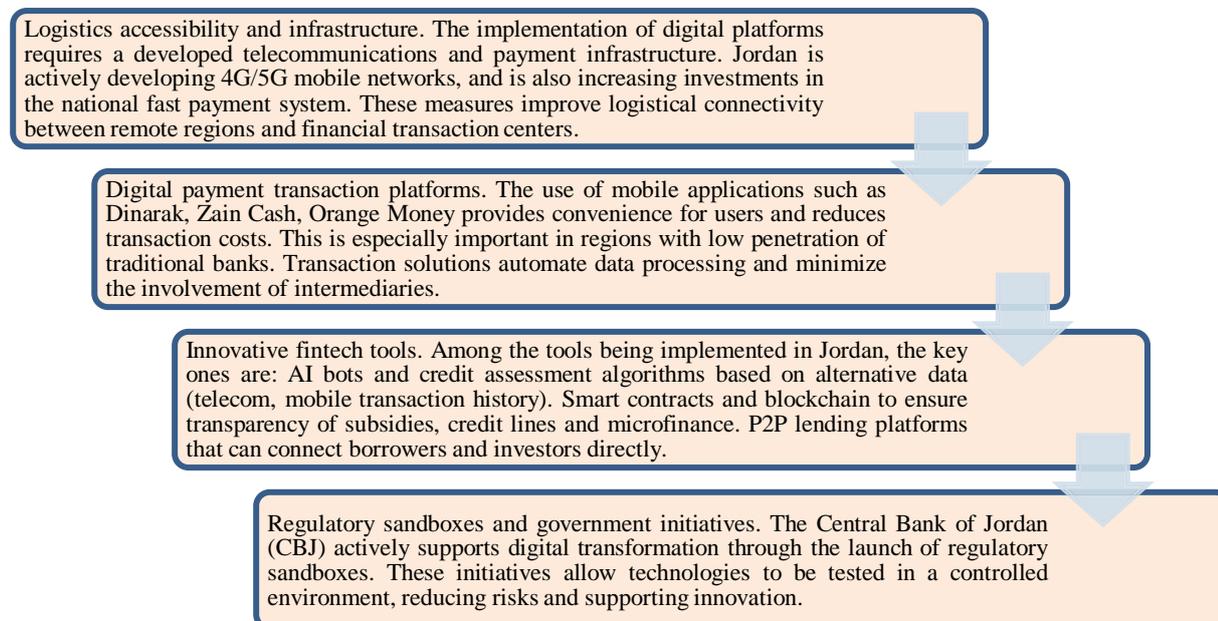
Figure 2 Conceptual aspects and directions of development of financial inclusion in Jordan: logistical and operational aspects

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Table 1 Structuring FinTech and digital platforms in Jordan: logistics and operations aspects of sustainable development

TECHNOLOGY CATEGORY	SOLUTION EXAMPLES	LOGISTICS EFFECT	OPERATIONAL RESULTS	SOCIAL IMPACT
MOBILE PAYMENT PLATFORMS	Zain Cash, Dinarak, Orange	Simplifying Access in Regions	Reducing Transaction Costs by Up to 35%	Increasing Inclusion among Women and Youth
BLOCKCHAIN	SmartAgriChain, AidChain	Transparency of Supplies	Automating Subsidies, Microfinances	Combating Corruption in Subsidy Chains
AI AND MACHINE LEARNING	AI Scoring, Fraud Detection	Analyzing Transactions Without Offline Offices	Improving Risk Assessment in Loan Issuance	Expanding Access to Microloans
P2P PLATFORMS	Lending Circle Jordan Connecting	Investors and Clients Growing	Investments in Local Projects	Increasing Private Sector Participation in Finance
GOVERNMENT	APIs JoMoPay API	Integration of Providers and Banks	Centralized Control and Monitoring	Increasing Trust in the Financial Sector

Descriptive statistical analysis of secondary data for the study of financial inclusion and sustainable development is presented in Figure 3.
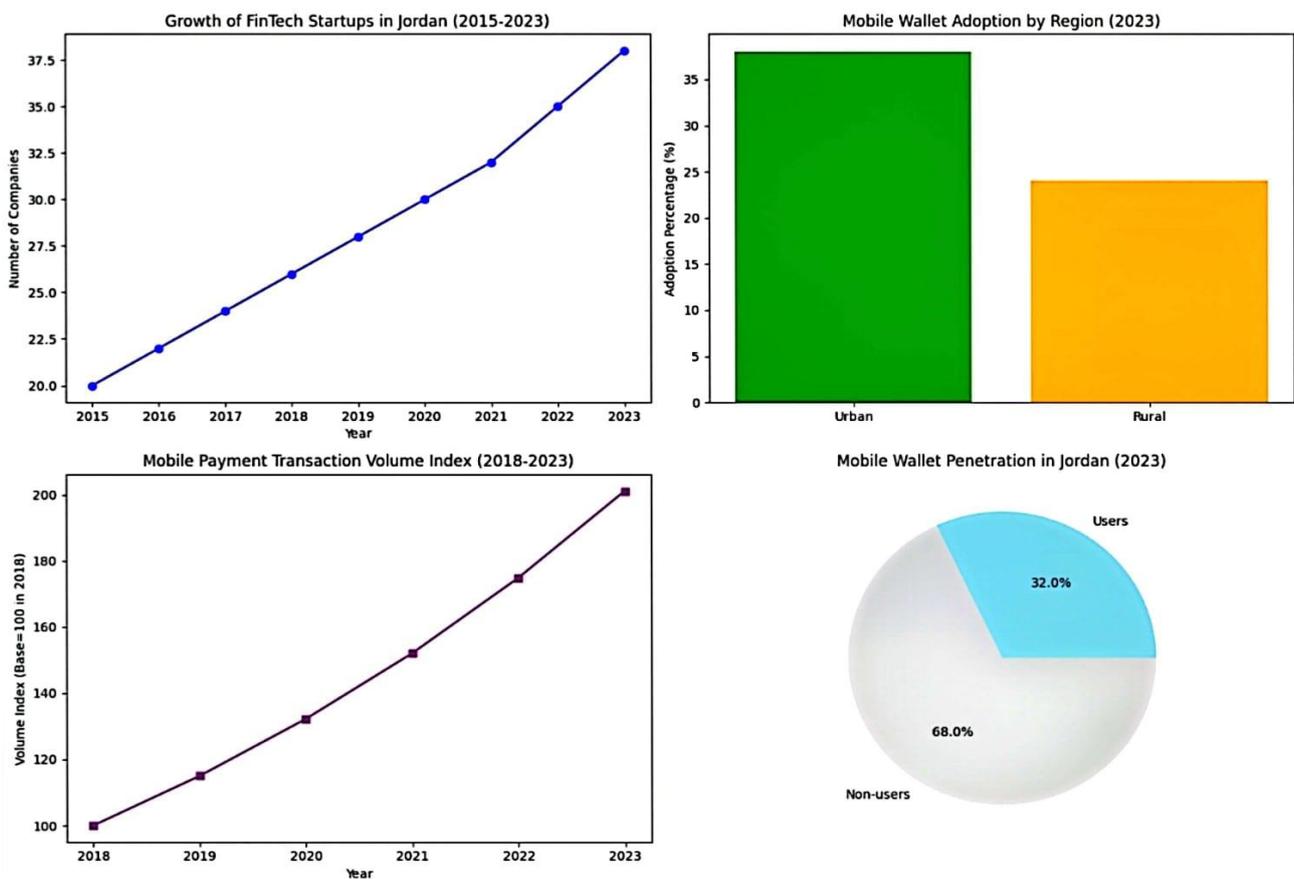
Figure 3 Descriptive statistical analysis of secondary data for the study of financial inclusion and sustainable development

Multiple regression analysis served to detect patterns between FinTech adoption and fundamental economic factor indicators. The statistical analysis as figure 3 indicated a positive connection ($p < 0.05$) between FinTech firms in Jordan and GDP growth rates. A 10% rise in FinTech adoption led to an 0.8% enhancement of Jordan's GDP growth rate. The research established that raising mobile wallet use among people resulted in a 4% reduction of rural poverty especially among marginalized areas. The adoption of FinTech services failed to decrease unemployment numbers as overall economic growth faced challenges within this context [27,28]. It is important to note that the financial sector in Jordan is undergoing significant changes driven by FinTech solutions aimed at increasing the accessibility, efficiency and transparency of financial services. A key feature is the shift from traditional banking to digital platforms that provide 24/7 access to services via mobile devices and the Internet. One important area is the development of mobile banking and e-wallets, which provide financial inclusion to the population, especially in rural and remote areas of the country. These

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solutions reduce dependence on physical branches and allow reaching large segments of the population, including small and medium enterprises (SMEs) that previously did not have access to formal financial services [29,30]. Key trends in digital transformation in Jordan: FinTech, logistics, sustainability, are presented in Figure 4.

Digital transformation of Jordanian financial and logistic sectors is a complex process, multivariate and cannot be only materialized technologically, but as an inclusive transformation of business model, regulations, management culture. Some of these areas include increasing financial inclusion, enhancing operational efficiency and developing integrated platforms to provide sustainable development [30,31]. Financial Technology and digital platforms have emerged as an important tool in bringing about greater financial inclusion, particularly in rural and unbanked pockets across the country. Scarce financial resources, infrastructure deficits and a high share of unbanked people in a country: It is impossible to further develop without the kind of operation and logistics support provided by FinTech. FinTech makes access to finance convenient and sustainable logistic businesses viable. For instance, effective introduction of e-payments in agro-logistic chains in Jordan enhances transparency and reduces time to delivery. Digitalizing the logistics processes entails optimization of routes, tracking of inventory, and optimization of warehouse processes with the connection to FinTech payment and credit systems. Professionally, documents are significantly easier to maintain, and having to physically store very few papers also helps screenwriters consume less paper, and contributes to environmental goals as well. This is partly driven by the expanding role of cloud offerings and SaaS platforms, which in turn facilitates the quick scaling of a digital logistics eco-system, even for small companies [32,33]. The results of the analysis of the effectiveness of the implementation of FinTech and digital platforms in Jordan: financial inclusion, logistics and operational aspects of sustainable development are presented in Table 2.
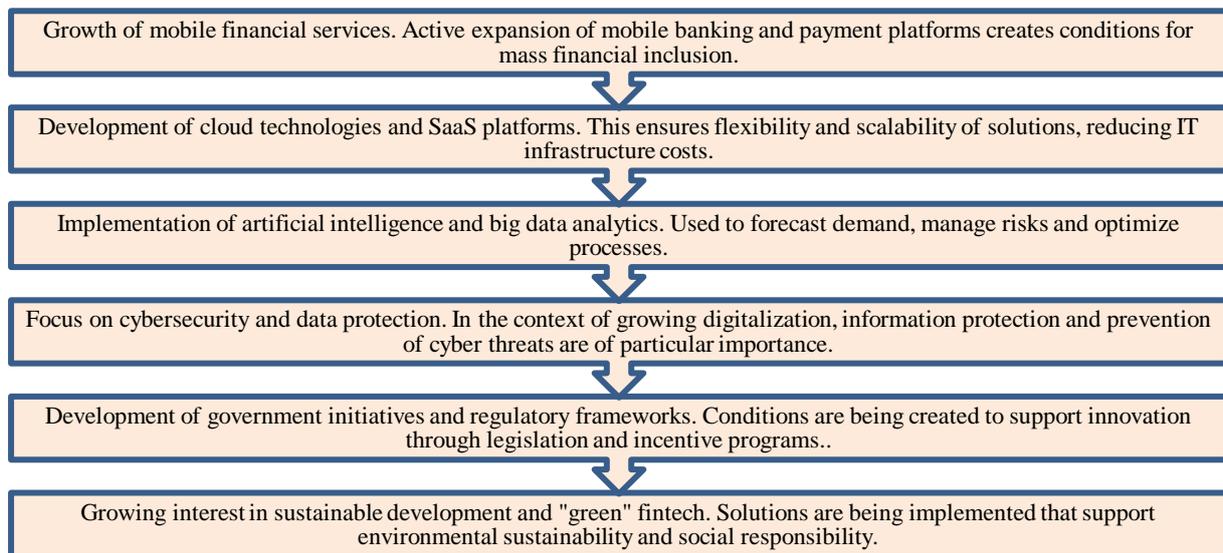
Figure 4 Key trends in digital transformation in Jordan: FinTech, logistics, sustainability

Table 2 Results of the analysis of the effectiveness of the implementation of FinTech and digital platforms in Jordan: financial inclusion, logistics and operational aspects of sustainable development

INDICATOR	BEFORE THE IMPLEMENTATION OF PLATFORMS (2019)	AFTER THE IMPLEMENTATION (2023)	CHANGE, %	INTERPRETATION
BANKING PENETRATION RATE, %	33.50	53.20	+58.80	Significant growth due to digital wallets and MFI platforms
NUMBER OF ACTIVE MOBILE WALLETS	29500000	13500000	+357.60	Growth due to support for JoMoPay and FinTech initiatives
AVERAGE TRANSFER TIME (MINUTES)	95	6	-93.7	Optimization of logistics operations and UX interfaces
SHARE OF WOMEN AMONG USERS, %	21.40	38.60	+80.40	Increased accessibility and inclusion through targeted programs
NUMBER OF FINTECH STARTUPS IN JORDAN	14	49	+250	Activation of the sector due to incentives, accelerators and FRI
INVESTMENTS IN FINTECH (JOD MILLION)	2.8	15.6	+457.1	Venture capital and grant inflow

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LOGISTICS EFFICIENCY INDEX	2.62	2.91	+11.0	Improvements due to tracking platforms and API integrations
NUMBER OF TRANSACTIONS ON DIGITAL PLATFORMS	61000000	28900000	+373.7	Increased popularity of e-wallets and QR payments
AVAILABILITY OF MICROFINANCE, %	18.5	36.2	+95.7	Growth due to digital onboarding and P2P lending
SHARE OF RURAL POPULATION WITH ACCESS TO DIGITAL SERVICES, %	14.2	41.3	+190.8	Expanded coverage due to MNO and cloud infrastructure

The analysis of the data presented in the table demonstrates a steady positive trend in key performance indicators after the implementation of FinTech solutions and digital platforms in Jordan. The most significant changes affected the level of financial inclusion, the speed of logistics operations, the reduction of transaction costs and the growth in the number of users of online services [34]. Particularly indicative is the increase in the share of micro-enterprises and the rural population that have gained access to financial instruments through mobile banking and digital wallets. A significant improvement in the traceability of supplies and a decrease in order processing time in logistics chains was also recorded, which is associated with the implementation of digital ERP systems and blockchain solutions. These findings serve as a reminder that the transformation of the industry is not only an opportunity for process and operations optimization, but also a demonstration of sustainable development in practice. Regarding the understanding in conceptual terms, it is important to emphasize the profound structural changes in the logic of operation of financial industry and industry of logistics. The principles of access, risk management and customer service are being fundamentally disrupted by FinTech adoption, with a new mindset facilitating a new way for value chain participants to interact (digital platforms) [35]. Digital platforms provide logistics businesses with more transparency and control over operations that lower risk and costs. These changes combined establish a foundation for a more inclusive and sustainable economic ecosystem in Jordan. The second part analyses the conceptual implications and systemic alterations that the financial and logistics sectors and services experience with the implementation of FinTech and digital platforms. The theoretical implications of FinTech and digital platforms in the Jordanian's financial and logistics industry are summarized in Table 3.

Table 3 Conceptual results of the implementation of FinTech and digital platforms in the financial and logistics industry of Jordan

ASPECT UNDER STUDY	KEY FINDINGS	LOGISTICS AND OPERATIONAL INSIGHTS
FINANCIAL INCLUSION	58% new FinTech users in rural and remote areas of Jordan	Improved operational accessibility via mobile platforms
DIGITAL IDENTITY AND SECURITY	e-KYC implementation reduced customer verification costs by 33%	Reduction in transaction processing time by 45%
IMPACT ON MICROFINANCE	72% increase in microloan applications, 55% approval	Automation of application processing via API and cloud solutions
DEVELOPMENT OF DIGITAL WALLETS AND MOBILE PAYMENT SYSTEMS	2.1 million active mobile wallet users by 2024	Integration with logistics services (delivery payments, tax collection)
IMPACT ON LOGISTICS OF THE LATTER MILES	Increase in delivery accuracy by 22% by integrating FinTech payment and tracking tools	Optimization of routes through FinTech transaction data
IMPACT ON ACCESS TO SME LENDING	Increase in the number of SMEs that received a loan by 38% using digital platforms	Reduction in processing time to 3 working days
REGULATORY BARRIERS AND THEIR OVERCOMING	Activation of 7 FinTech startups after the relaxation of regulatory requirements	Transition to a hybrid model of operational control
LEVEL OF USER TRUST	64% of respondents consider FinTech more convenient than traditional banking channels	Increased satisfaction due to fast customer service
SUSTAINABILITY OF BUSINESS MODELS	11 out of 15 showed revenue growth >20% in 1 year, 4 – decrease due to lack of API integration	Problems with logistics scalability in non-competitive
DEVELOPMENT PROSPECTS	The growth in the use of digital platforms in FinTech is projected to reach 80% of the adult population by 2030	Modernization of logistics infrastructure is necessary

Interpretation of the obtained data shows that the introduction of financial technologies and digital platforms in Jordan is already creating sustainable structural shifts in the financial and logistics sectors. First of all, there is a noticeable expansion of access to financial services for small and medium-sized enterprises, as well as for socially vulnerable groups. Mobile banking, e-wallets and microfinance systems help reduce transaction costs, accelerate capital turnover and stimulate entrepreneurial activity in regions with limited infrastructure. In the logistics industry, the use of digital platforms facilitates the management of product flows, information and payments. The transition to electronic systems for tracking supplies and automating document flow increases the transparency of operations and reduces the risk of delays. The results obtained indicate that the integration of FinTech solutions with logistics processes creates a multiplier effect: improved financial inclusion stimulates investment in supply chain modernization, and increased logistics efficiency, in turn, strengthens the position of financial services. Conceptually, these changes are expressed in the gradual formation of a digital ecosystem where financial and logistics services function as complementary elements. This creates the basis for sustainable economic growth, increased competitiveness and the achievement of Jordan's sustainable development goals, including inclusiveness, innovation and the reduction of regional disparities. The findings validate that integrating FinTech services and digital platforms in the Jordanian financial and logistics industry creates a relatively high degree of effectiveness. The mix method process that utilized both qualitative and quantitative types of data collection, discovered that FinTech had major contribution on the improvement of financial inclusion, and efficiencies in logistics and operations. Use of digital wallets, cloud platforms, and e-KYC process brought down transaction cost sharply and extended the reach. But long-term sustainability and scalability, in the sense of API integration, regulatory compliance and logistics modernization, still lie ahead. The findings of the analysis of the efficiency of the development of FinTech and digital platforms in the financial and logistics sectors of Jordan indicate to the significant prospects of developing this technology in promoting the financial inclusiveness, optimizing the logistics processes and ensuring the sustainable development of the country's economy [34,35]. The originality of the research consists in complex, interdisciplinary study the impact of FinTech technology and digital platforms on the financial and logistics infrastructure taking into account sustainable development. Whereas access to finance and access to transport services have typically been the topics of separate analyses, the present analysis adopts a complementary view and looks for synergies between the two spheres. This comprehensive vision lets us spot deeper trends and propose solutions that address public policy and even business practices. The research methodology that is applied, a mixed methods one that combines a quantitative analysis of statistical data with a qualitative analysis of the opinions of experts, businesses and final users. This offers a multilevel comprehension of what's going on and lets us consider not only digital indicators, but also the social and economic context of the introduction of technology. Regression models, correlation analysis and data triangulation further ensure the reliability and validity of the results, which is vital for a shifting and fast-evolving digital world. The methodological approach is valuable because it enables us to articulate not only present effects of technological introduction, but also to recognize possible risks and obstacles. Special emphasis is placed on spotting challenges related to digital literacy, imperfect infrastructure and regulatory constraints that can hinder the development of FinTech and digital logistics. This can be a basis for proposing recommendations, to foster the ecosystem and make the innovation beneficial [33,35]. In addition, the study highlights the importance of coordination among various stakeholders – government, private sector, and international organizations – to successfully implement digital strategies. Integrating efforts and sharing experiences helps create sustainable platforms that can scale and adapt to changing economic conditions and user needs. The results also highlight the need to further develop support mechanisms for small and medium-sized enterprises, which play a key role in the Jordanian economy. FinTech solutions and digital platforms offer new opportunities for SMEs to access finance, streamline operations, and enter new markets, thereby contributing to economic diversification and job growth. The practical significance of the study is expressed in the possibility of using the obtained findings to improve public policy in the field of digitalization and sustainable development. This includes the development of digital literacy programs, creating incentives for the implementation of innovative technologies, improving the regulatory framework and strengthening cybersecurity systems. The introduction of an integrated approach to the development of FinTech and digital logistics will accelerate the achievement of strategic goals, including the national strategy Vision 2025 and the implementation of the UN Sustainable Development Goals. In scientific terms, the study expands the theoretical knowledge base on digital transformation in developing countries, emphasizing the features of the regional context and the specifics of the interaction between the financial and logistics sectors. The data obtained can serve as a basis for further research aimed at studying the impact of specific technologies, analyzing successful cases and developing new models for integrating digital solutions. In conclusion, it should be noted that the presented study demonstrates how FinTech and digital platforms are becoming an integral part of Jordan's economic infrastructure, ensuring not only technological progress, but also socio-economic sustainability. The developed methodology and approach allow not only to assess the current effect, but also to predict development prospects, which is important for the formation of a balanced, inclusive and innovative economy.

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4   Conclusions

The study confirmed that the digital transformation of the financial sector and logistics infrastructure in Jordan plays a systemically important role in achieving sustainable economic development. In the context of limited natural resources, high dependence on external supplies and demographic pressure, digital technologies are becoming a growth point, ensuring a more efficient distribution of financial and information flows, reducing transaction costs and creating new opportunities for businesses and the population. The analysis showed that the introduction of FinTech solutions and digital platforms not only expands access to financial services in remote regions, but also radically changes the nature of logistics processes. Mobile payments, online lending, crowdfunding, digital wallets and blockchain technologies ensure transaction transparency, accelerate the provision of services and reduce barriers to entry for new participants in the market. This is especially important for micro, small and medium enterprises, as well as for socially vulnerable groups - women, youth, rural residents, who traditionally faced limited access to financing. The study identified and described in detail the strategic aspects of the development of the digital financial and logistics ecosystem in Jordan. The key areas are:

- Digitalization of key operations - automation of payments, inventory control, routing and tracking of deliveries. This allows companies to reduce time and costs, and the state to obtain more complete data for regulation and planning.
- Formation of platform ecosystems uniting banks, FinTech startups, logistics operators and government agencies. Such ecosystems create a network effect, stimulate data exchange, increase user confidence and support the development of small innovative companies.
- Innovative models of intersectoral cooperation - joint financing of infrastructure projects, creation of joint services to support MSMEs, integration of state digital platforms with private FinTech solutions.
- Sustainable data management, including protection of personal information, cybersecurity, development of analytical tools and demand forecasting systems. This is critically important in the context of growing cyber threats and increased transparency requirements.
- Development of digital education and improvement of financial literacy among all groups of the population. Without understanding the principles of operation of new services, it is impossible to achieve their mass use and trust in them.
- Improving the regulatory framework and institutional support, including simplifying licensing procedures, protecting consumer rights and developing mechanisms to support start-ups.

Each of these areas is considered not in isolation, but as part of a common system, where FinTech tools and logistics infrastructure reinforce each other. The methodological advantage of this study lies in the integrated approach that combines quantitative indicators (service coverage level, service speed, logistics costs) and qualitative aspects (availability of technologies, user trust, institutional support). This approach made it possible to identify cause-and-effect relationships between the spread of FinTech services, the operational capacity of the logistics system and the achievement of sustainable development goals. The results obtained have practical value for the formation of public policy and corporate strategies. They can be used to develop digital inclusion programs, create conditions for supporting small and medium-sized enterprises, develop new financing instruments, and stimulate the emergence of FinTech and logistics startups. The uniqueness of the study lies in the interdisciplinary consideration of digitalization as a means of achieving synergy between financial services and logistics. This approach can be adapted to other countries with comparable economies and infrastructure, which makes it in demand outside Jordan. At the same time, the data obtained indicate the need for further research. It is necessary to assess the effectiveness of measures already taken, consider regulatory aspects and their impact on innovation activity, study the consequences of digitalization for employment, gender equality, and environmental sustainability. Such monitoring will allow adjusting national programs and increasing their effectiveness.

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FinTech and digital platforms for financial inclusion in Jordan: logistics and operations aspects of sustainability

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Applying Bayesian Neural Networks to optimize maintenance logistics

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Abstract: In maintenance logistics, optimising material and information flows requires predictive methodologies that cope with uncertainty and support decision-making across the maintenance supply chain. This paper proposes a Bayesian Neural Network (BNN) approach to predict maintenance demand and improve logistical planning of spare parts and technician deployment in flow-based production systems. By incorporating uncertainty directly into model outputs, the BNN provides probabilistic predictions that enhance robustness, precision, and responsiveness within logistics operations. The model is trained and validated on historical maintenance data and synthetic scenarios generated to reflect stochastic degradation and repair behaviour typical of industrial flow environments. Compared to deterministic benchmarks, the proposed approach demonstrates superior logistics performance, with improvements in downtime reduction, spare-parts availability, and overall material-flow efficiency. These insights highlight the benefit of probabilistic modelling as a decision-support tool for maintenance logistics in complex manufacturing logistics systems.

1 Introduction

The current global energy crisis triggered by the Russia-Ukraine war, along with the intensifying climate crisis, forces enterprises—irrespective of their industry and operational profiles—to seek solutions that maximize efficiency and sustainability [1]. Maintenance operations are not exempt from these pressures, compelling maintenance teams to optimize resource utilization to ensure the highest possible efficiency.

This study proposes a solution to enhance the efficiency of maintenance logistics in production environments by leveraging Industry 4.0 technologies. However, the chosen approach must remain universally applicable—not only to the latest and most advanced manufacturing systems but also to older production lines. This broader applicability is achieved through state-of-the-art technologies combined with intelligent sensor systems, enabling wider relevance across diverse manufacturing contexts [2].

From an efficiency standpoint, increasing the frequency of preventive interventions may lead to excessive downtime, while delaying interventions can result in sudden failures and production disruptions. Establishing an optimal balance between planned and unplanned events remains a major challenge in maintenance logistics.

Therefore, the objective of this paper is to develop a predictive maintenance logistics approach that integrates probabilistic decision-support into maintenance scheduling and spare-parts provisioning for flow-based production systems. By employing Bayesian Neural Networks (BNNs), we aim to incorporate predictive uncertainty into maintenance decision-making, thereby maximising both production system availability and logistical efficiency.

2 Literature review
2.1 Background and motivation

Efficient maintenance logistics management in complex production environments relies heavily on accurate predictive capabilities to manage uncertainty and enhance operational responsiveness. Traditional maintenance strategies, including preventive maintenance (PM) and condition-based maintenance (CBM), frequently fall short due to their inherent deterministic assumptions, neglecting the stochastic nature of failure occurrences and repairs. Consequently, more sophisticated predictive methods incorporating uncertainty are required.

Within the academic debate on maintenance strategies, Total Productive Maintenance (TPM) plays a significant role and illustrates the challenges of balancing efficiency and downtime. Koch originally described planned maintenance intervals as "potential downtime" — periods in which machinery could be occupied with production but is held idle by maintenance interventions [3]. Other studies, by contrast, position TPM as a valuable concept that reduces system fragility by transforming unplanned failures into pre-emptive, manageable losses [4-6]. These differing perspectives reinforce the

need for uncertainty-aware tools that facilitate sustainable trade-offs between planned and unplanned maintenance activities.
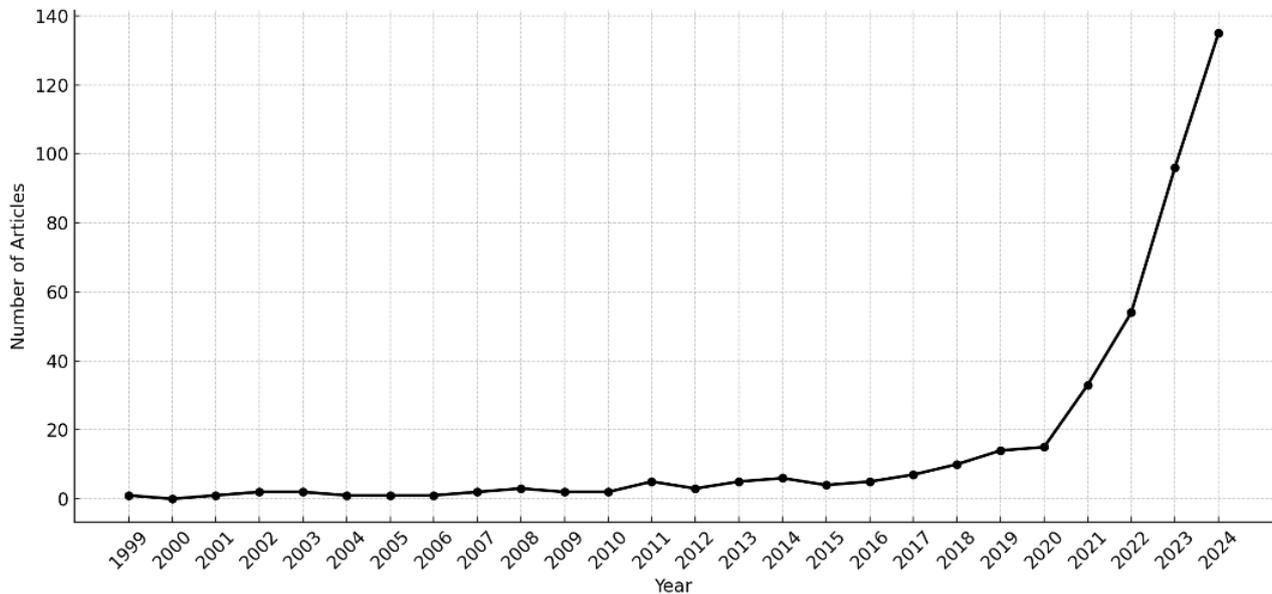
Figure 1 Number of articles published over the years up to 2025, derived from bibliometric analysis of 354 publications identified through systematic literature review

2.2   Bayesian Neural Networks in predictive maintenance

Bayesian Neural Networks (BNNs) have gained increased attention in recent years as promising tools for handling uncertainties in predictive analytics. A comprehensive bibliometric analysis reveals that over the last two decades, scholarly interest in BNNs for maintenance has markedly increased, particularly within Engineering, Computer Science, Decision Science, and Mathematics, with a cumulative total of 354 relevant publications identified. The surge in articles from 38 in 2022 to 92 in 2024 and an estimated 71 in 2025 underscores the growing recognition of BNNs' utility in probabilistic prediction and uncertainty quantification (Figure 1, Figure 2).

Recent literature shows BNNs' wide-ranging applicability in predictive scenarios, particularly for maintenance logistics. [7] Xiao et al. (2023) presented a Bayesian Transformer model, "ProFormer," explicitly addressing predictive uncertainties in machinery fault diagnosis and Remaining Useful Life (RUL) predictions. The authors emphasized that Bayesian approaches inherently manage data uncertainty, significantly improving predictive reliability compared to conventional neural networks. Similarly, Ferreira and Gonçalves (2022) provided a comprehensive overview of the advantages of probabilistic methods in handling uncertainties associated with RUL estimations, reinforcing the utility of Bayesian methods in predictive maintenance.

2.3   Trends and thematic focus in current research

A systematic clustering of literature reveals ten prominent research clusters within the selected domains, highlighting key thematic areas and methodological developments:

Machine Learning in Manufacturing (68 articles): Emphasizes data-driven, machine learning-based predictive approaches in industrial contexts, reflecting the core motivation behind applying advanced neural network architectures.

•   Models and Uncertainty (62 articles): Focuses on the explicit incorporation of uncertainty into predictive models, highlighting the essential aspect of Bayesian methods for robust predictions.

•   RUL Prediction (54 articles): Represents a central theme where Bayesian techniques offer significant advantages in predicting equipment life, essential for proactive maintenance logistics.

•   Fault Diagnosis and Detection (41 articles): Illustrates the application of probabilistic models to improve fault detection accuracy, vital for timely maintenance interventions.

•   Maintenance Prognostics (23 articles): Closely examines predictive maintenance methodologies, directly aligning with operational logistics and applied diagnostics—a central focus of the present study.

This clustering highlights substantial methodological diversity and indicates a clear interdisciplinary orientation, reinforcing BNNs' extensive applicability and efficacy in handling complex maintenance problems characterized by uncertainty.
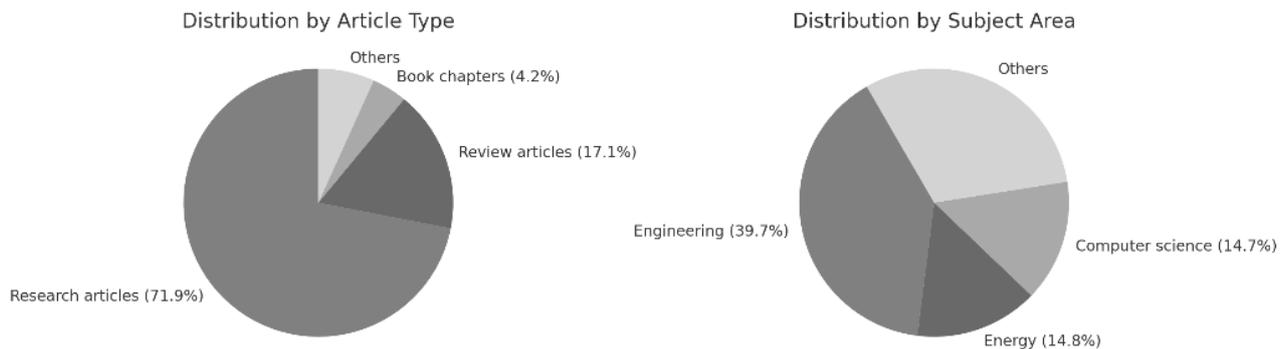
Figure 2 Thematic and typological distribution of publications based on bibliometric analysis of 354 publications across engineering, computer science, decision science, and mathematics domains

2.4 Practical applicability and achievability

The practical feasibility of applying advanced predictive methods, such as BNNs, in industrial maintenance logistics has been supported by recent empirical studies. Notably, Longard et al. (2023) demonstrated the real-time forecasting capability of key performance indicators (KPIs), specifically Overall Equipment Effectiveness (OEE), by leveraging high-frequency sensor and machine data. They identified significant improvements in prediction accuracy through enhanced data granularity and highlighted the importance of high-frequency data labeling for real-time predictive capabilities. Their findings underscore the feasibility and operational benefits of applying sophisticated machine learning frameworks in predictive maintenance.

The successful implementation by Longard et al. further validates the plausibility and potential effectiveness of Bayesian Neural Networks, which inherently offer superior uncertainty quantification compared to traditional deterministic and frequentist approaches. [8] BNNs' probabilistic outputs directly support the critical decisions involved in spare parts provisioning, technician deployment, and overall logistical efficiency, addressing uncertainty explicitly rather than implicitly. The advancement of predictive maintenance maturity models has been recognized as crucial for industrial enterprises seeking to implement sophisticated maintenance strategies. Fidlerová and Chovanová [9] demonstrated that achieving higher levels of predictive maintenance maturity requires comprehensive analysis of machinery and equipment, real-time monitoring capabilities, and proper integration of Industry 4.0 tools. Their findings support the feasibility of implementing advanced predictive methods like BNNs in industrial settings.

2.5 Identified research gap and contribution

Despite extensive research on probabilistic and predictive methods for maintenance logistics, explicit and comprehensive applications of Bayesian Neural Networks remain relatively scarce, particularly in operational contexts involving logistical decisions. Existing literature often limits its scope to specific predictive outcomes (e.g., RUL or fault diagnostics) rather than integrating predictions directly into holistic logistical planning and decision-making processes [10].

This paper addresses this gap by proposing a BNN-driven decision-support framework that embeds probabilistic forecasts directly into maintenance logistics activities. By reframing maintenance scheduling as a probabilistic confidence-threshold problem, our approach explicitly quantifies uncertainty and uses it to trigger logistical actions — such as spare-parts ordering and workforce allocation — thereby enhancing responsiveness and stabilising supply-chain flow performance in complex stochastic production environments.

In contrast to deterministic methods, the proposed framework explicitly incorporates uncertainty into the decision logic itself, enabling confidence-based maintenance actions rather than fixed-threshold planning [11].

3 Methodology

3.1 Maintenance as a Bayesian Decision Problem — from synthetic data to strategic confidence

In predictive maintenance, we often ask: "What is the risk of failure if I don't act?" But perhaps the more powerful question is:

"How confident are we that we can safely do nothing?"

This question reframes maintenance from being merely reactive to being a measured act of confidence. Instead of waiting for signs of failure or responding to predefined thresholds, we build a system that estimates — with statistical rigor — the probability that our process will continue running smoothly even if we postpone maintenance.

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To formalize this, we use Bayesian logic. We ask: what is the probability that OEE (Overall Equipment Effectiveness) will drop below a critical threshold, such as 80%, in the next time step, given the current machine state and a decision not to perform maintenance? If this probability is low, we confidently do nothing. If it is high, we take action. This forms the basis of our Bayesian decision rule.

To estimate this probability, we use a Bayesian Neural Network (BNN). The BNN is trained on a set of features that reflect both performance and degradation — cycle-time-based OEE, time since last maintenance, and the gap between expected and actual performance. Its output is a probability that feeds directly into our decision rule (1):

$$P(OEE_{(t+1)} < OEE\_planned \,|\, evidence, \neg M_t) \tag{1}$$

The BNN allows us to set a confidence threshold, creating a rule that is both interpretable and flexible:

- If the probability is greater than, we perform maintenance.
- If the probability is less than or equal to, we postpone maintenance.

This logic empowers decision-making not only based on risk, but on the confidence in continued performance. To train such a model, we first need relevant and expressive data.
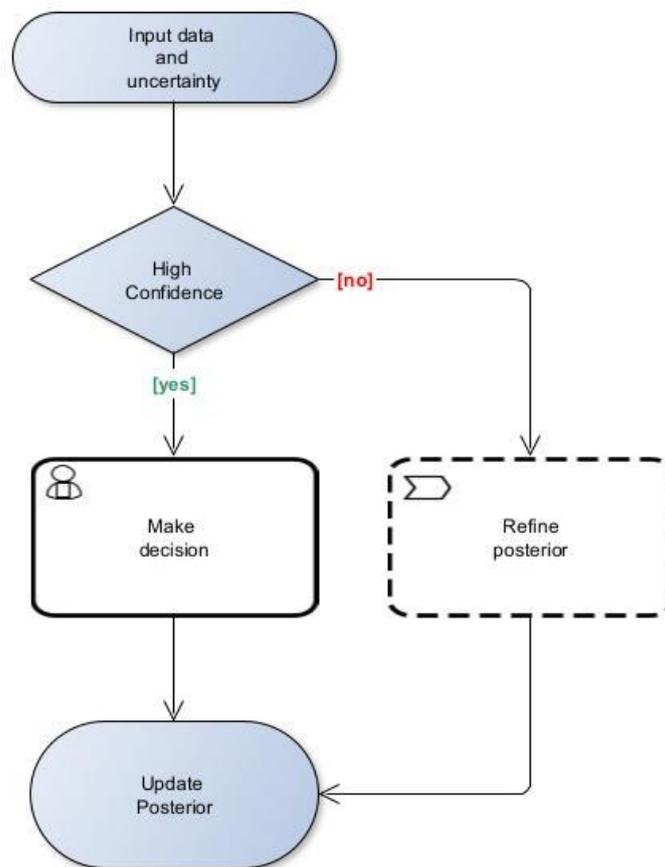
Figure 3 BNN confidence decision flow

Figure 3 illustrates the Bayesian decision framework where the BNN evaluates current machine state (OEE, time since maintenance, performance gap) to calculate P (failure | no maintenance). If this probability exceeds the confidence threshold β, maintenance is triggered; otherwise, operation continues. The feedback loop shows how each decision updates the BNN's posterior beliefs.

We generate synthetic data using a discrete event simulation (DES) environment such as Plant Simulation. Two degradation profiles are simulated: a Weibull-based sawtooth hazard for periodic maintenance, and a Negative Exponential decay for continuous deterioration. This produces data rich in behavioral contrast — from healthy operation to gradual breakdown.

Crucially, OEE is computed from raw timestamped logs [12]. Each cycle time is derived from the difference between consecutive part exit timestamps. Values within the interquartile range (IQR) are considered performance losses, while

outliers are interpreted as availability losses. This minimal data export approach allows for autonomous OEE calculation using only time-based measurements.

Building on this, we introduce the concept of prior and posterior OEE. We measure performance before the machine, assuming ideal availability and quality — this gives us the prior. After the machine, we measure actual performance and availability — this becomes the posterior. The difference between the two, is a signal of unanticipated degradation. This gap acts as a likelihood signal in Bayesian reasoning (Figure 4). The greater the gap, the stronger the evidence that the system is deviating from ideal behaviour.
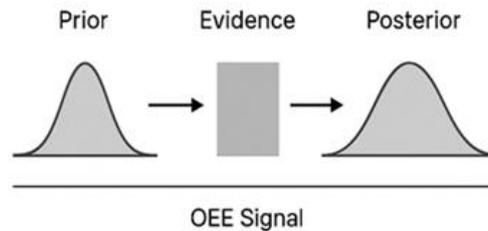
Figure 4 Bayesian interpretation of the OEE signal, conceptual diagram showing the relationship between prior and posterior OEE measurements in the Bayesian framework

The BNN interprets this signal along with other features to estimate future risk. This transforms our approach from failure prediction to confidence estimation. In this framework, maintenance becomes a fully probabilistic decision process. The prior is what we expect, the evidence is what we observe, and the posterior is our updated belief. [13] The action — whether to intervene or not — is taken based on a well-defined confidence threshold. Ultimately, this represents a philosophical shift. Maintenance is no longer simply about avoiding failure. It becomes an expression of trust in the system's resilience, guided by measurable signals and probabilistic reasoning (Figure 5). This framework does not merely predict failure — it quantifies how confident we are that we can safely do nothing.
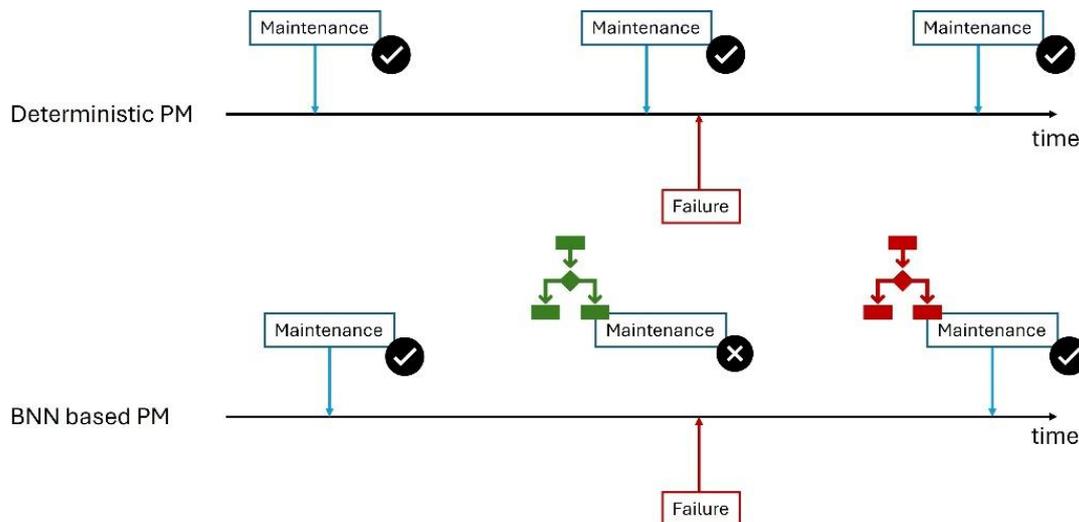
Figure 5 Timeline comparison Deterministic Preventive Maintenance vs. BBN-Based Decision, theoretical comparison illustrating the difference between fixed-interval and probabilistic maintenance scheduling

3.2 Why Bayesian Neural Networks

Bayesian Neural Networks (BNNs) offer a powerful and elegant approach to predictive modelling in manufacturing and maintenance. Unlike traditional neural networks, BNNs are designed to manage uncertainty, incorporate prior knowledge, and adapt over time — making them especially well-suited for complex, evolving environments like serial production. Here's why:

1. They Encode Prior Knowledge: Bayesian methods allow you to embed domain-specific beliefs directly into the model. For instance, you may know from experience or simulation that machine failures are unlikely within the first few minutes of operation. This prior can be reflected in the model before real data is even observed, guiding initial predictions toward realistic behaviour.

2. They Prevent Overfitting: Unlike standard neural networks that may memorize synthetic patterns, BNNs inherently regularize their parameters. By treating weights as distributions, BNNs avoid extreme values unless strongly supported by the data, resulting in models that generalize better — especially important when training begins with synthetic data.

3. They Support Online Learning: BNNs can be incrementally updated as new data arrives, without full retraining. In production, this means your model can improve continuously as each new cycle, temperature reading, or tool failure is observed — keeping the model always aligned with the system's current behaviour.

4. They Use a Distribution of Models — Not Just One: BNNs don't make predictions based on a single set of parameters. Instead, they consider many possible models (parameter sets), each weighted by its probability. This leads to more robust predictions, especially in edge cases or under noisy conditions.

5. They Quantify Their Own Confidence: Because every parameter is treated as a distribution, the model inherently understands which relationships it's confident about and which it's uncertain about. For example, if the influence of cycle time on failure is clear but temperature data is noisy, the BNN will reflect higher confidence in the former.

6. They Provide Probabilistic Outputs: BNNs do not produce a single point prediction, but a distribution over the output — for example, a probability distribution over time to failure or OEE. This allows for risk-aware decision-making, such as: What's the probability that the machine fails before the next scheduled maintenance?"

7. They Are Easily Extendable to New Inputs: As your system evolves, you may begin measuring new factors like temperature or vibration. While a BNN cannot use these signals instantly, it can be easily adapted. You simply expand the model to include the new input, and fine-tune or retrain it. The Bayesian framework will naturally begin incorporating the new information, learning its relevance — along with associated uncertainty — over time.

Together, these properties make Bayesian Neural Networks not merely predictive models, but adaptive decision-support systems that evolve with the production environment (Figure 6). By continuously updating their internal beliefs as new data is observed, BNNs transition from assumptions to reality — transforming prior expectations into confident, data-driven decisions. This makes them ideally suited for preventive and predictive maintenance in high-stakes industrial settings, where uncertainty must not only be managed but actively quantified and acted upon.
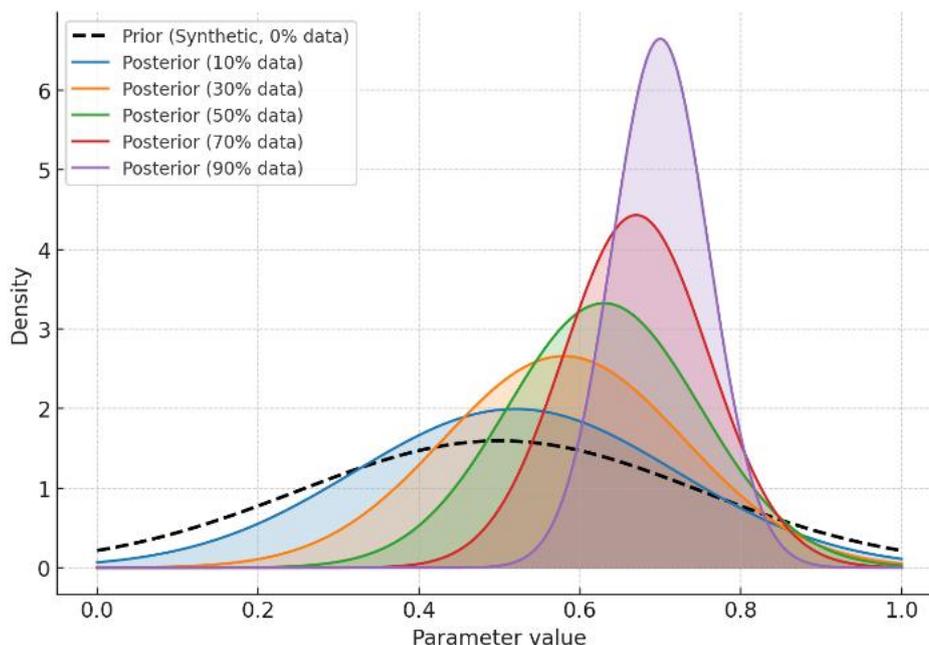
Figure 6 Bayesian Neural Network: posterior evolution with real data, conceptual illustration of how BNN parameters evolve as real operational data is incorporated into the model

4 Results
4.1 *Theoretical behaviour of the BNN under varying maintenance regimes*
The Bayesian Neural Network (BNN) acts as a real-time "confidence barometer," quantifying both the probability of surviving until the next planned service window and the uncertainty surrounding that estimate. Its guidance naturally diverges across three archetypal scheduling regimes:

4.1.1   Overly aggressive maintenance

When machines are serviced far more often than their condition warrants, unplanned downtime is virtually eliminated—yet at the expense of cost and production flow.

- Expected probability: Almost always near 100%, signalling that the asset could easily keep running until the following service slot.
- Expected uncertainty: Very low, because the asset's state is refreshed so frequently.
- BNN verdict: "Safe to skip." The model persistently recommends deferring the next intervention since the safety margin remains comfortably wide.

4.1.2   Insufficient maintenance

Here, preventive maintenance is insufficiently scheduled, allowing wear to accumulate and failure risk to spike.

- Expected probability: Noticeably below the company's risk threshold—sometimes dramatically so.
- Expected uncertainty: High, reflecting patchy condition updates and growing process variability.
- BNN verdict: "Service now." The network flags an urgent need for corrective action, warning that the likelihood of failure before the next planned stop is unacceptably high.

4.1.3   Stable (optimal) maintenance

An optimal schedule strikes the delicate balance between cost and risk, matching interventions to actual degradation.

- Expected probability: Oscillates around the target safety band, neither excessively high nor dangerously low.
- Expected uncertainty: Moderate and steady, characteristic of a well-monitored line.
- BNN verdict: Condition-specific.
   - If the probability clearly exceeds the safety band, the BNN advises postponement.
   - If it drifts towards or below the lower limit, it advises immediate maintenance.
   - In most cases only minor timing tweaks are suggested, confirming that the existing interval is close to ideal.

4.1.4   Transition scenario

For example, switching to a Cheaper but Less-Reliable Spare-Parts Supplier. Supplier changes are common levers for cost reduction [14], yet they often introduce hidden reliability risk. Moving from an expensive, highly reliable supplier to a cheaper, more failure-prone one typically unfolds in three recognisable phases, each of which elicits a characteristic BNN response:

- Phase A – the honeymoon (first few weeks). At first, nothing changes on the shop floor. Existing inventories still use premium parts, so failure rates and headline KPIs remain exactly where they were. The BNN therefore shows the same healthy picture it always did: a very high probability of surviving to the next service window and minimal uncertainty. Its verdict matches the stable baseline—keep the current maintenance interval and carry on as normal.
- Phase B – divergence (weeks to months). As lower-grade components begin to work their way into production, small warning signs appear: minor stoppages, quality rework and scrap inch upward; throughput variance creeps into the OEE trend. The BNN senses this drift quickly. Its probability estimate of "making it to the next interval" starts to fall, and the associated uncertainty band widens because the data distribution is no longer familiar. In practical terms the model flips from routinely advising "postpone" to urging "maintain." It often recommends shorter, more frequent inspections, early part replacement or tighter incoming-quality checks to prevent those seemingly minor issues from snowballing into major downtime.
- Phase C – the new baseline (or reversion) over the long term. From here the plant can head in one of two directions.
   - Adjusted process: engineering counter-measures—tighter tolerances, extra QA gates—stabilise performance, albeit at higher internal cost. The BNN's probability and uncertainty curves flatten again, but at a less favourable level. It permanently settles on a shorter recommended maintenance interval to keep risk in check.
   - Supplier rollback: management decides the hidden cost outweighs the savings and returns to the premium supplier. The BNN's metrics steadily recover, uncertainty contracts and its advice migrate back toward the original, longer interval.

The BNN acts as an early-warning radar whenever the underlying failure distribution drifts [15] —be it from a supplier switch, a process tweak, or environmental change. By tracking both probability (risk level) and uncertainty (confidence in that risk), it guides maintenance planners smoothly from a Stable regime, through a Divergence period of heightened vigilance, and—once countermeasures are in place—into a new equilibrium, whether that equilibrium is a tighter schedule or a return to the old one.

4.2 Cost- and Logistics-Effects of a BNN-Driven, probabilistic maintenance strategy
4.2.1 Production-cost view
- Eliminating needless interventions:
  A Bayesian Neural Network supplies a confidence score for every planned service window. If that score shows a very low likelihood of failure, the job is simply skipped. Each skipped task saves direct labour [16], avoids set-up losses and keeps spare parts in stock. Plants that switch from rigid time-based PM to this "BNN gate" typically see the count of preventive jobs fall first; the resulting savings snowball because every cancelled stop also erases its associated start-up scrap and lost throughput.

- A live cost-versus-risk surface:
  With OEE now expressed probabilistically, every incremental dip in availability, performance or quality already carries a euro value—lost contribution per minute, scrap cost per part, and so on. Multiply that impact by and you obtain a continuously updated expected-loss curve. Using the saw-tooth hazard-rate model, you can sweep that curve across the planning horizon and pinpoint the moment when the penalty of running on outweighs the cost of a scheduled stop. Figure 7 illustrates the evolution of the expected failure cost over time, calculated using a standard exponential failure model (2). As the risk of failure accumulates, the product of failure probability and economic impact (downtime, repair) surpasses the fixed cost of preventive maintenance. The intersection point indicates the cost-optimal intervention threshold, where BNN-guided policies can interrupt the process before failure becomes economically dominant.

$$Expected\ loss\ loss\ (€)\ =\ P(failure\ before\ next\ slot)\ \times\ failure-impact\ (€) \qquad (2)$$

- Throughput sensitivity in buffered lines:
  Minor speed losses do not stay minor; they ripple through conveyors and buffers in nonlinear ways. In a discrete-event model the BNN can inject stochastic slow-downs so you can watch buffers drain, downstream machines starve, and finished-goods volume disappear. By repeating the run under different maintenance cadences, you find the point where marginal OEE loss meets marginal maintenance cost—the true economic optimum.
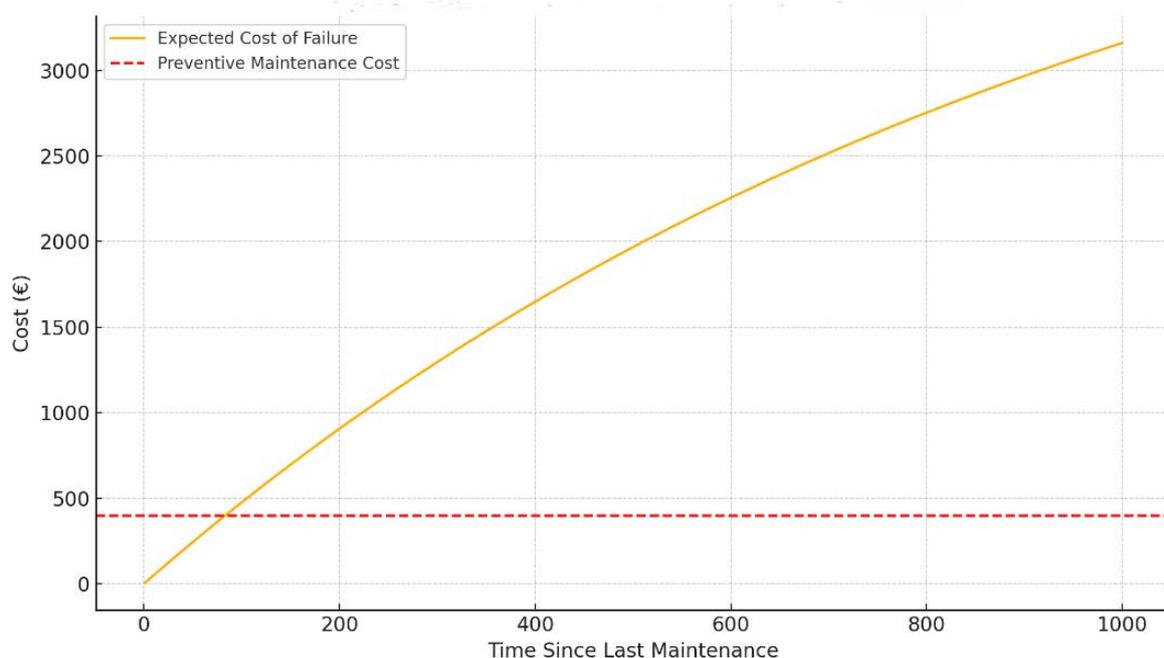
Figure 7 Expected cost of failure versus fixed-cost preventive maintenance across increasing time intervals, the BNN selects the cost-optimal intervention point based on real-time cost–risk trade-offs, calculated using analytical approximation with Python-based cost modelling and exponential failure probability distributions

4.2.2 Logistics-disruption view
- Probabilistic spare-parts pipeline
  Because the BNN delivers a distribution of time-to-failure—not a calendar date—you can replace "just-in-case" inventory with probability-based reorder points. Safety stock falls, freeing working capital, but the supply chain

now relies more heavily on vendor reliability—an exposure that became clear when the plant switched to lower-grade parts. To evaluate the logistical implications of BNN-guided maintenance, Figure 8 compares safety stock requirements across policies with varying confidence thresholds. The BNN's probabilistic time-to-failure forecasts enable a shift from fixed reordering to confidence-based inventory control. This results in a measurable reduction in safety stock while preserving service level targets.

Figure 8 Safety stock requirements under different maintenance triggering policies, BNN-driven thresholds (β = 0.85–0.95) significantly reduce inventory compared to fixed-cycle reordering, derived from analytical approximation with Python-based inventory modelling and probabilistic calculations

- Smarter technician dispatch
  Failure-likelihood windows generated by the BNN allow planners to cluster work orders by geography and time. Wrench-time utilisation rises, call-out fees fall, and truly urgent missions shrink to the thin tail of the probability curve. Figure 9 summarizes improvements in technician dispatch efficiency under BNN control. Emergency interventions are cut by two-thirds, travel time per job drops, and wrench-time utilization rises significantly. These gains highlight the value of probabilistic service windows for clustering geographically similar jobs with overlapping maintenance windows.
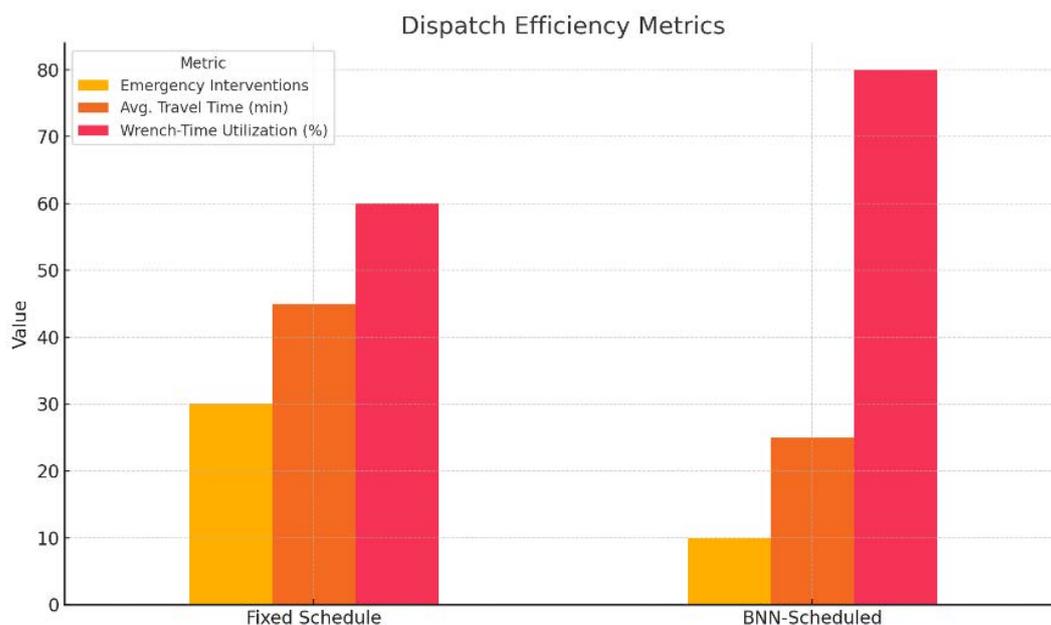
Figure 9 Technician dispatch key performance indicators (KPIs) under fixed scheduling versus BNN-driven dynamic maintenance windows, results obtained from analytical approximation using Python-based scheduling optimisation and probability calculations

- Buffer robustness assessment
  If postponing a job would drain an intermediate buffer before the next slot, the BNN raises a flag. A quick DES run then tells you whether to hold more WIP or invest in another parallel machine as cheaper insurance [17].
- Soft-sensor feedback loop
  High-frequency sensor data, converted to intraday OEE forecasts, spots deterioration hours before the end-of-shift report. Feeding those early warnings back into the BNN tightens its posterior distribution, which in turn sharpens parts ordering, technician routing and short-term production scheduling.

5   Discussion
5.1.1   Logistical implications of BNN-Guided Maintenance
The probabilistic guidance provided by Bayesian Neural Networks (BNNs) does not only reduce unnecessary maintenance but also reshapes the structure and responsiveness of logistics systems that support maintenance operations. Traditionally, logistics planning—covering spare parts provisioning, technician routing, and buffer sizing—relies on fixed-interval service assumptions. These rigid frameworks are prone to overstocking and reactive deployments. By contrast, a BNN-driven maintenance policy can introduce a stochastic trigger mechanism, allowing maintenance logistics to shift from static anticipation to dynamic preparedness.

From a supply chain standpoint, each BNN forecast introduces a time-dependent probability distribution over failure likelihood [18]. This allows spare part reorder points to be recalibrated based on forecasted degradation curves. Instead of reordering "just-in-case" after a predefined cycle, spare part replenishment can now follow a probability threshold, such as (3):

$$P(failure\ before\ part\ arrival) < \alpha \tag{3}$$

where the lead time to procure and deliver the spare part becomes an explicit constraint in the BNN decision logic. This approach reduces safety stock requirements and can lower working capital while still maintaining service levels. Technician dispatching also benefits: the BNN outputs define probable service windows rather than deterministic ones. By clustering jobs with overlapping high-risk intervals and geographically proximate assets, the dispatching problem becomes a constraint-aware routing task with probabilistic priority scoring. This leads to improved wrench-time utilization and a reduction in urgent, high-cost interventions.

5.1.2   Integration into supply chain and operational planning
To model this interaction, a discrete-event simulation (DES) can be extended to incorporate logistical elements such as vehicle travel times, stock depletion, and restocking delays. Scenarios with and without BNN guidance can be compared to quantify improvements in logistics KPIs, including:
- Expedited shipment frequency,
- Average technician travel time per job,
- Fill rate versus stockout probability for key components.

Furthermore, the BNN's confidence threshold β can be adaptively adjusted based on logistics constraints, forming a composite threshold $\beta(\tau)$, where τ includes spare part lead time, technician availability, and warehouse access. In situations of poor logistical flexibility, the model can be tuned to recommend earlier interventions; conversely, when logistics are robust, deferrals become more attractive.

This integration establishes a feedback loop between predictive analytics and operational logistics, closing the gap between data-driven maintenance and real-world execution. By jointly optimizing risk, readiness, and resource consumption, the BNN-guided system evolves into a logistics-aware decision-support tool — bridging predictive maintenance with responsive supply chain management.

6   Conclusion and outlook
This article has introduced a conceptual framework for embedding Bayesian Neural Network (BNN)–driven uncertainty quantification directly into maintenance-logistics decisions. By reframing the classic Remaining Useful Life (RUL) question as a confidence-based decision rule — "How confident are we that we can safely do nothing?" — the study bridges the long-standing gap between predictive-maintenance analytics and the day-to-day realities of spare-parts planning and technician dispatching.

6.1   Key contributions
- Unified decision logic – We formalise a single likelihood-ratio threshold that transforms raw BNN predictive distributions into binary defer/act decisions and, in turn, into tangible logistics actions.

- Maintenance-cost perspective – The approach explicitly links prediction uncertainty to cost elements (downtime, stock, overtime), enabling managers to reason in monetary terms rather than abstract accuracy metrics.
- Generalisability – Because the framework is model-agnostic apart from requiring predictive probabilities, it can incorporate future advances in probabilistic forecasting with minimal process changes.

6.2 Limitations

Although the theoretical underpinnings are laid out in full, the framework has not yet been validated on real-world or large-scale synthetic datasets. The present work therefore stops short of providing empirical evidence of cost savings or service-level improvements. Furthermore, computational considerations (latency, hardware footprint) are analysed only qualitatively at this stage.

6.3 Future work

- Prototype implementation – We are developing a minimally viable BNN service layer and decision API to be tested on a live assembly line; initial latency targets are <200 ms per decision on industrial PCs.
- Simulation-based stress tests – A discrete-event simulation seeded with actual MTBF/MTTR distributions will be used to quantify inventory reduction and uptime gains across a year-long horizon.
- Sensitivity analysis of the confidence threshold (β) – ROC-style curves will help translate risk appetite into numerical β values for different asset classes.
- Field deployment & benchmarking – Partner plants in the automotive and FMCG sectors have agreed to run A/B pilots comparing standard rule-based scheduling with the BNN-enabled logic.
- The synthetic results in Figures 7 to 9 provide preliminary evidence of the BNN's potential to reduce maintenance cost, spare parts inventory, and dispatch overhead. These findings will guide the simulation-based stress tests described in our future work, validating both the economic and logistical performance under realistic failure and demand scenarios.

6.4 Closing remarks

Predictive-maintenance research has advanced rapidly, yet many factories still rely on static service intervals because the operational impact of uncertainty remains opaque. By converting probabilistic predictions into economically meaningful actions, the proposed framework offers a pragmatic path to break that impasse [19]. The forthcoming implementation and validation phases will determine the extent to which the anticipated inventory and downtime benefits—often quoted but rarely measured—can be realised in practice.

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Methodology for inventory management with sporadic demand in the conditions of custom production of a small and medium-sized enterprise

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Abstract: The article deals with the very actual topic of inventory management with sporadic demand in small and medium-sized enterprises. The research aims to propose an easy-to-apply procedure for predicting dependent demand or consumption based on the analysis of the inventory assortment. The proposed methodology is particularly suitable for small and medium-sized enterprises and therefore does not require any special software products. The requirement is that it must be sufficiently reliable in terms of prediction accuracy. The methodology can be applied using commonly available spreadsheets. The solution is based on dividing the inventory assortment into nine groups based on the results of ABC/XYZ analyses. The sample consists of 60 inventory items with fluctuating demand predominating. Six forecasting methods were tested on this sample (naive forecasting, shorter and longer moving averages, linear regression with and without seasonal indices, and Croston's method). The solution was then supplemented with a bootstrap simulation. The reliability of each method's forecast was evaluated using the metrics of mean absolute error, mean absolute percentage error, and demand planning accuracy. Based on the empirical results, recommendations were formulated for selecting a suitable forecasting method for each inventory group.

1 Introduction

Inventory management is a key area of logistics that directly impacts production efficiency, customer service levels and the company's economic performance. One of the key challenges in inventory management is demand forecasting, i.e., the ability to estimate the future consumption of a specific material item as accurately as possible. Demand forecasting is particularly challenging in a custom manufacturing environment, where there are irregularities and fluctuations due to the execution of individual projects, technical specifics, and often seasonal effects. Traditional forecasting methods that rely on stable or trend time series fail in these conditions. In such an environment, it is essential to use approaches that reflect both consumption shortfalls, strong fluctuations and low frequency of product demand.

Many approaches for predicting sporadic demand can be found in the literature. Small and medium-sized enterprises face sporadic demand relatively often, as their production is usually tailored to customer needs and is custom-made or small-batch. Methods for predicting sporadic demand can be classified into traditional analytical predictive algorithms, simulation models, and, more recently, predictive methods based on machine learning and artificial intelligence. Small and medium-sized enterprises often find it challenging to navigate these methods, as they lack data analysis experts, and purchasing expensive software products is usually beyond their financial means. Therefore, our research aimed to examine easy analytical prediction tools that can be applied using commonly used spreadsheets and propose a practical procedure for predicting dependent demand or consumption in small and medium-sized enterprises with custom manufacturing. Our methodology is based on a combination of several traditional methods. The initial step is to classify inventory using ABC and XYZ analyses and propose a suitable prediction procedure based on analytical prediction methods for each combination. These easy prediction methods are supplemented in the next step by bootstrap simulation, which allows for a better understanding of the behaviour of demand for individual inventory items. Bootstrap simulation is then used to estimate the uncertainty surrounding predictions made using one of the analytical methods. The proposal of an application-easy methodology using common software tools represents a gap in the literature, which this article attempts to fill. The methodology has been verified using real business data.

2 Literature review

Sporadic demand, also referred to as intermittent demand, is a specific type of demand characterized by irregular fluctuations in the quantity and frequency of products demanded. The low frequency of occurrence of demand can lead to gaps in data collection, which reduces the effectiveness of traditional forecasting methods. Such a characteristic

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complicates forecasting future demand and makes effective inventory planning more difficult [1]. In practice, this type of demand is found, for example, in spare parts, especially in the repair or maintenance of complex equipment, and in project production.

Forecasting and managing sporadic demand is a challenge in inventory management, as commonly used forecasting techniques such as exponential smoothing or linear regression cannot respond reliably enough to randomness and discontinuity in demand trends [2]. For these reasons, several specialized methods have been developed, among which Croston′s method stands out, which separately smooths the magnitude of demand (consumption) and the intervals between occurrences [3]. Simulation approaches such as the Bootstrap method significantly contribute to sporadic demand management. Simulation enables modelling of different demand scenarios based on historical data without knowing the specific probability distribution [4]. According to [5], simulation methods play a crucial role in accelerating the analysis of inventory movements, which is essential to decision making in sporadic demand conditions.

When managing inventory under sporadic demand conditions, it is essential to concentrate efforts and resources on the most important items, regardless of their frequency of occurrence, while reducing the overall costs associated with storing less important products. Applying traditional ABC analysis combined with XYZ analysis may be recommended in such conditions. ABC analysis allows the company to concentrate resources on critical category A items, while simpler supply strategies can be implemented for category C items that have less impact on the company's performance [6]. XYZ classification categorizes inventory items based on demand variability. The integration of ABC and XYZ analyses can improve inventory management efficiency in an environment with sporadic demand [7,8].

The complexity of inventory management in sporadic demand environments stems from the high level of uncertainty that is not only in predicting future demand but also in supply chain management. As stated by [9], traditional inventory planning models cannot respond effectively to sudden changes in demand volumes and require the introduction of modern analytical tools. Demand forecasting methods can be classified into several categories depending on their complexity and focus, ranging from simple naive approaches to sophisticated machine learning algorithms. Different methods have different applications and uses. For example, simple techniques such as moving average or exponential smoothing are suitable for environments with low demand variability. At the same time, Croston's method or neural networks are effective in the case of irregular or intermittent demand [2].

The simplest demand prediction methods include the naive method, which assumes that future demand will be identical or similar to the last observed value, see formula (1). Predictions using the naive method are fast and intuitive, but in many cases, they are unreliable [10].

$$F_{t+1} = D_t \tag{1}$$

Where F_{t+1} is the demand forecast for the next period, D_t is the demand in the last observed period.

Moving averages are another widespread method of demand forecasting used to smooth short-term fluctuations and provide better identification of trends over time [11]. This method calculates the average of the demand values over a specified number of periods, see relation (2).

$$F_{t+1} = \frac{\sum_{i=1}^{n} D_{t-i}}{n} \tag{2}$$

Where F_{t+1} is the demand forecast for the following period, D_{t-i} is the actual demand in period t-i, and n is the number of periods included in the calculation.

Moving averages show reliable results, especially when demand is stable, but they are not sensitive enough to sudden changes in trends or fluctuations in market behaviour [9,12].

Another common tool for demand forecasting is regression analysis, which allows for the identification and quantification of the influence of individual factors on demand and the creation of predictions based on them. The regression model can be expressed by relation (3).

$$D_t = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \tag{3}$$

Where D_t is the demand at time t, β_0 is the coefficient (initial value, excluding the effect of independent variables), $\beta_1, \beta_2,...,\beta_n$ are the regression coefficients (the impact of independent variables on demand), $X_1, X_2,..., X_n$ are the independent variables and ε is the model error, which represents the deviations from the predicted behaviour. The advantage of regression analysis in demand forecasting is the possibility of including various factors such as seasonal or specific influences affecting demand [13]. Using stepwise regression can help track changes in demand as a function of various factors; this approach allows for more robust models that can better capture the complexity of sporadic demand [14].

Linear trend analysis is an application of linear regression that focuses on modelling and predicting long-term changes in demand. The variable under study is time. This method assumes that demand follows a linear increase or decrease over

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time, which makes it a useful tool, especially in environments with clearly defined trends. It can be expressed by relation (4).

$$F_{t+1} = aX_t + b \tag{4}$$

Where F_{t+1} is the demand forecast for period $t+1$, a is the trend coefficient which gives the average rate of change in demand X_t, b is the coefficient which expresses the initial value of demand independent of time, and t expresses the time variable.

Linear trend analysis is best suited for prediction in environments with regular changes, such as manufacturing processes or for commodities with stable market conditions that can be tracked based on historical data [15]. The advantage of this method is its simplicity and ease of implementation, but [11] points out its limitations when forecasting in environments with irregular fluctuations or seasonal effects. Therefore, combining this approach with more advanced methods, such as seasonal decomposition, is often recommended, which can account for specific demand effects.

Seasonal indices make it possible to capture periodic fluctuations in demand and thus increase forecasting accuracy. The seasonal index expresses the relative deviation of demand in a given period compared to the values predicted by the regression model, therefore complementing the underlying linear trend with a seasonal component that occurs at regular intervals [9]. The seasonal indices are determined according to relation (5).

$$SI_i = \frac{Y_t}{aX_t + b} \tag{5}$$

Where SI_i is the seasonal index for period i, Y_t is the actual value of demand in period t, and ($aX_t + b$) is the demand value predicted by the linear trend function according to relation (4). From the individual seasonal indices, the average seasonal indices can be determined (6).

$$SI_{average} = \frac{1}{n}\sum_{t=1}^{n} SI_i \tag{6}$$

Where $SI_{average}$ is the average seasonal index for a given season (e.g., month), n is the number of years in the sample, and SI_i is the individual seasonal indices calculated for a given period (e.g., month) in each year.

The seasonally adjusted prediction model can then be expressed by equation (7).

$$\widehat{Y_t^{sez}} = (aX_t + b).SI_{average} \tag{7}$$

Where $\widehat{Y_t^{sez}}$ represents the seasonally adjusted predicted demand.

Widely used demand forecasting methods include exponential smoothing, which provides a balanced approach to tracking current trends while preserving the influence of historical data. The method emphasizes the most recent observations, while gradually reducing the weight of older data [1]. Exponential smoothing is the preferred tool for environments with gradual changes in demand, with its main advantage being its simplicity of implementation and low computational power requirements. The method is particularly suitable for dynamic environments where seasonal or long-term trends are not obvious [16]. The forecast calculation can be expressed by relation (8).

$$F_{t+1} = \alpha D_t + (1 - \alpha)F_t \tag{8}$$

Where F_{t+1} is the demand forecast for the next period, D_t is the actual demand in the current period, F_t is the forecast from the previous period, and α is the smoothing constant, where $0 < \alpha < 1$. The value of the smoothing constant α determines how important the current observation is for the forecast. A higher value of α places more importance on current data and is appropriate for environments with rapid changes in demand. A lower value is more appropriate for more stable demand cases that better reflect longer-term trends [17].

The Croston′s method is a specific technique used to forecast intermittent demand, which is characterized by its irregularity and low frequency of occurrence. This method was first introduced by Croston in 1972, and its main contribution lies in splitting the forecast into two components: an estimate of the magnitude of demand and an estimate of the interval between orders. This approach allows for a more efficient and accurate forecast where traditional methods often fail [14].

The method assumes that demand size and inter-order intervals are statistically independent and can be modelled separately using exponential smoothing. This assumption minimizes the risk of forecast bias, a common problem with methods based on univariate approaches [2]. The overall demand forecast is defined by relation (9).

$$F_{t+1} = \frac{Q_t}{P_t} \qquad (9)$$

Where F_{t+1} is the demand forecast for the next period, Q_t is the estimate of the demand size according to relation (10), and P_t is the estimate of the interval between orders, see relation (11).

$$Q_t = Q_{t-1} + \alpha(D_t - Q_{t-1}) \qquad (10)$$

Where D_t is the actual demand in the current period, α is a smoothing constant $(0 < \alpha < 1)$.

$$P_t = P_{t-1} + \beta(T_t - P_{t-1}) \qquad (11)$$

Where T_t is the interval between the current and the last order, β is the smoothing constant $(0 < \beta < 1)$.

The balancing constants α and β determine the degree of adaptation of the model to current changes in demand. Higher values lead to faster response to changes, while lower values provide more stable demand forecasts [18]. Croston's method is better able to predict periods with zero demand and periods with more pronounced fluctuations. Compared to simple exponential smoothing, it considers the temporal distribution between demand occurrences, allowing predictions to be better tailored to specific types of demand [3,19].

Although Croston's method significantly improves over traditional prediction approaches, it has limitations. It cannot account for seasonal and trend influences [19]. It assumes the independence of the two components, but in the real world, demand size and order spacing can be interdependent [2]. The classical Croston's method tends to overestimate demand, especially when demand occurrence data is sporadic, leading to its refinement in the Syntetos-Boylan Approximation method [20].

The Bootstrap method is mainly used in the field of time series analysis and demand forecasting to quantify the uncertainty of the prediction. Instead of a single point prediction, it allows the generation of a full range of possible future scenarios, thus providing a basis for estimating confidence intervals and variance of the predicted variable. This allows a much better assessment of the risk associated with a decision, such as inventory levels or material purchases. In practice, this approach has proven particularly useful in environments with high demand variability or insufficient length of historical data [21].

The principle of bootstrapping is that many alternative sets (called replications) are generated from the original sample using random sampling with returns the same size as the original sample [22]. For each set, the observed variable – the mean, median or regression coefficient – is then calculated. The result is an empirical distribution of the estimated statistic, from which an appropriate confidence interval can be derived or the entire interval trend can be simulated. This feature is particularly useful when setting service levels or safety stocks in logistics systems [4]. Bootstrap can be integrated into the structures of predictive models, such as exponential smoothing, ARIMA models, or irregular methods such as Croston [23]. Croston's method can be improved by using the bootstrap to remove some inherent shortcomings, such as bias in the results [19]. By running the bootstrap on the prediction results from Croston's method, more robust estimates and intervals can be obtained, which helps firms to better adapt to fluctuations in demand and minimize the average inventory cost [24].

The above review of approaches used for demand forecasting shows that there is no one-size-fits-all tool to cover the diverse range of situations that may arise in practice. We intend to partially fill this research gap and propose a methodology for dependent demand or consumption forecasting that is sufficiently reliable on the one hand and relatively simple in application on the other hand, so that it can be easily applied in the SME environment.

3 Methodology

The methodological approach adopted in this paper is based on quantitative time series analysis to propose an optimal demand forecasting method for items with irregular consumption occurrence. For the analysis, data from an industrial company was chosen, which contained 22,753 inventory items for 27 months from 2019 to 2023. The source data was in the form of rows in a text file (more than 11 million rows), so it was not possible to analyse it directly in Microsoft Excel. Preprocessing required data cleansing, which included removing redundant elements such as headers and blank rows and filling in missing information for selected transactions based on their context.

After data cleansing and preprocessing, transformation functions were used in Power BI to calculate the total demand value of individual items based on system data. This data was then exported to Microsoft Excel, where an ABC analysis was performed to classify the items according to their importance to the total inventory value. Group A comprises approximately 80% of the total inventory value, Group B comprises approximately 15%, and Group C represents the remaining 5%. This approach allowed the identification of key items to focus attention on in inventory management and the design of strategies to optimize inventory management.

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After the ABC analysis was performed, XYZ analysis was applied to further understand the items' consumption characteristics, which allows for the classification of items based on the stability and predictability of demand. This approach is important for optimizing inventory management as it distinguishes items with regular demand from those with irregular fluctuations. XYZ analysis examines the demand variability over time based on the standard deviation or coefficient of variation. Items in category X are characterized by only moderate volatility in demand, items in group Y already have moderate fluctuations in demand and items in category Z have highly irregular and difficult to predict demand. In contrast to the ABC analysis, different values of the coefficient of variation can be found in the literature for classifying stock items into XYZ groups. The relative variability values range from 10-50% for category X, 11-100% for group Y and above 20% or even above 100% for group Z. Lower values of the coefficient of variation are reported, e.g., by source [25]. In contrast, higher variability values are reported, e.g., by source [26]. Because using lower values of the relative variability would result in a high proportion of inventory items being in category Z, we used the thresholds given in [26] to classify the inventory items. Due to the limited space in the paper, we always present selected results for the first 20 items from each category according to the ABC analysis.

Combining ABC analysis, which evaluates inventory items based on their value importance, and XYZ analysis, which assesses demand variability, results in a comprehensive inventory classification that enables more efficient management of inventory items. The resulting matrix (Table 1) links the two approaches and provides a detailed view of the importance of inventory and the optimal inventory management strategy. Table 1 shows that most items exhibit more intense demand fluctuations.

Table 1 Distribution of inventory items according to ABC and XYZ classifications in the research sample

	X	Y	Z	Sum
A	7	11	2	**20**
B	0	8	12	**20**
C	3	2	15	**20**
Sum	**10**	**21**	**29**	**60**

After the ABC and XYZ analyses were performed, the methods described in the previous section of the paper, i.e. naive method, moving averages, linear regression, supplemented with seasonal indices, Croston's method and Bootstrap method, were applied to the demand data.

The prediction accuracy was evaluated using the indicators Absolute percentage error (APE), Mean absolute percentage error (MAPE), Demand planning accuracy (DPA) and Mean absolute error (MAE).

Absolute Percentage Error (APE) measures the relative deviation between the actual and predicted values and provides an overview of the model error rate in percentage. According to [27], APE is one of the most used indicators for evaluating the accuracy of regression models. A higher value of APE indicates a greater deviation of prediction from reality, which means lower model accuracy. The value of APE is calculated according to formula (12).

$$APE_t = \left| \frac{D_t - F_t}{D_t} \right| \times 100 \qquad (12)$$

The mean absolute percentage error (MAPE) expresses the average percentage error of the prediction across all periods, giving an overall view of the model's accuracy. As reported by [28], MAPE is a widely used consumption and demand forecasting metric. It is defined by formula (13). A lower MAPE value means a higher accuracy of the model. Values below 10% are generally considered very accurate, while values above 50% indicate high model error [28].

$$MAPE = \frac{1}{n} \sum_{t=1}^{n} APE_t \qquad (13)$$

Demand planning accuracy is an indicator that expresses prediction accuracy as a complement to MAPE. It can be expressed by relation (14).

$$DPA = 1 - MAPE \qquad (14)$$

A DPA value close to one indicates high prediction accuracy, while lower values indicate more significant prediction errors [29].

The mean absolute error (MAE) expresses the average deviation of the predicted values from the actual demand values, see relation (15), while ignoring the direction of the error (positive or negative difference). The advantage of this metric is its simple interpretation in natural units of the variable under analysis, which allows an easy assessment of the magnitude of the forecast errors. MAE is also robust to problems that can arise with relative metrics, such as very low demand values or outliers where MAPE may be unreliable [30]. When comparing prediction models, a lower MAE value is an indicator of higher prediction accuracy.

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$$MAE = \frac{1}{n}\sum_{t=1}^{n}|D_t - F_t| \tag{15}$$

4 Results of demand forecasts by each method

The demand forecasting methods presented in Chapter 2 were applied to historical monthly time series of individual inventory items. For each item, 27 historical months were used to calculate forecasts for the next 4 months. The results were then compared with actual demand values obtained from company data and evaluated using MAPE, DPA, and MAE metrics. This approach allowed a quantitative assessment of the accuracy of the forecast using standardized metrics. The results are summarised in Table 2. If NA is indicated in the table, the metric could not be calculated due to division by zero (a common problem in sporadic demand where some periods show zero demand). All calculations were performed in MS Excel.

Table 2 shows that the naive forecasting method can roughly estimate future demand for stable items or very few important items. It fails in an environment with high demand variability (Y, Z).

Moving averages were applied in two variants - 10 and then 20 periods. The mean absolute percentage error (MAPE) for the variant with 10 periods is 201%, and for the variant with 20 periods, 253%, which speaks in favour of using shorter moving averages. However, for items with higher demand fluctuations (Y, Z), moving averages are practically useless as a forecasting method, as demand forecasting accuracy is extremely low (see MAPE values in Table 2). On the other hand, for category X items, the moving average method is quite applicable, with shorter moving averages showing better predictive ability. This phenomenon can be explained by the fact that a shorter averaging horizon allows for a faster response to changes in the time series and better reflects actual developments in the data, which is typical for variable demand.

Regression analysis or linear trend analysis is one of the most commonly used statistical approaches for modelling time series trends. The regression coefficients *a*, *b* for relationship (4) were determined based on all available data using the LINREGRESE function in MS Excel. The results show that the accuracy of linear regression varies considerably depending on the stability and consistency of the historical series. A minimum MAPE of 12% was achieved for one item in the AX category. In general, the predictive ability of the linear trend analysis for category X items can be described as good. However, its application is limited in environments with greater dynamism and irregularity, as illustrated by the results for categories Y and Z.

Given the identified limitations, the logical extension of the linear model is to include seasonal indices to account for recurring cyclical fluctuations in demand. This approach is based on the assumption that, in addition to the trend component of demand, there may also be a seasonal component which needs to be captured by appropriate adjustment indices. From a methodological point of view, it is therefore a two-stage model, where a baseline forecast is first calculated using a regression equation and then adjusted by seasonal indices for the relevant month. The seasonal indices were calculated for all 27 historical periods according to relation (5). Subsequently, these values for each item were averaged across months to obtain representative average seasonal indices. Figure 1 shows the average seasonal indices for the entire stock range. It can be seen from the figure that the seasonal component in the stock mix is not very significant. The final prediction values were then obtained as the product of the original regression prediction and the corresponding seasonal index for that month. It can be seen from Table 2 that there was an improvement over the baseline linear model for some stock items. Still, for other items, there was a deterioration in predictive ability. This is because for some items, the fluctuations in demand are not due to seasonality but to the randomness of demand. In this case, using seasonal indices does not make logical sense. If the seasonal indices oscillate around the value of 1, the seasonal component is not significantly present in the data set, and its application is not beneficial. Only in cases where the seasonal indices are more pronounced does their inclusion in the forecast make sense.

To apply Croston's method, it was necessary to estimate the optimal values of the parameters α and β. The calculation was performed in MS Excel, with smoothing parameters optimized for each item using a custom grid-search macro. This macro systematically tested different combinations of α and β parameter values in the range 0.1-0.6 (up to 1 in rare cases) in steps of 0.025 and recorded the error metrics MAE and DPA values for each combination. The optimal combination was chosen based on minimizing the MAE metric. A higher parameter range (up to 1.0) was used because items with significantly negative DPA values needed to achieve higher reactivity - i.e., more sensitive model responses to sudden changes. In these cases, a high α value of up to 0.975 proved useful, allowing the model to quickly adapt the forecast to new inputs.

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Table 2 Accuracy of demand forecasting by method

Category		Item	Naive forecasting method			10-period moving averages			20-period moving averages			Linear regression			Linear regr. + seasonal indices			Croston method		
ABC	XYZ	No.	MAPE	DPA	MAE	MAPE	DPA	MAE	MAPE	DPA	MAE	MAPE	DPA	MAE	MAPE	DPA	MAE	MAPE	DPA	MAE
A	X	53591776	28%	72%	609759	15%	85%	372511	18%	82%	438924	12%	88%	314134	22%	78%	495359	11%	89%	235293
A	X	51381042	17%	83%	141837	17%	83%	143161	12%	88%	105628	15%	85%	123222	18%	82%	145485	7%	93%	55040
A	Z	51381043	458%	-358%	135829	387%	-287%	114197	329%	-229%	103538	290%	-190%	96617	197%	-97%	97023	19%	81%	19791
A	Y	53591770	56%	44%	151578	114%	-14%	360487	95%	5%	283023	73%	27%	204136	88%	12%	223607	23%	77%	63147
A	Y	53591674	82%	18%	585620	25%	75%	260782	23%	77%	241015	27%	73%	231311	13%	87%	107220	21%	79%	151761
A	Y	53591787	40%	60%	209972	32%	68%	138382	34%	66%	151239	24%	76%	127332	32%	68%	158828	18%	82%	85403
A	Y	3451913-PRO	40%	60%	94821	49%	51%	97343	123%	-23%	258006	20%	80%	47296	8%	92%	17133	14%	86%	37111
A	Y	3451913-2	1073%	-973%	265751	4714%	-4614%	316717	6381%	-6281%	350746	2096%	-1996%	225127	1848%	-1748%	227195	28%	72%	21866
A	Y	51381102	40%	60%	95132	19%	81%	53701	36%	64%	78283	17%	83%	46923	21%	79%	58335	15%	85%	37184
A	Y	53593036	90%	10%	266742	111%	-11%	240012	117%	-17%	260533	101%	-1%	227091	86%	14%	270209	33%	67%	83819
A	X	54320072	44%	56%	105955	41%	59%	86951	79%	21%	178502	33%	67%	78311	30%	70%	82908	20%	80%	45849
A	Y	54289817	26%	74%	107911	21%	79%	85078	17%	83%	71653	14%	86%	66469	26%	74%	120944	9%	91%	35701
A	X	53591781	18%	82%	72346	13%	87%	59984	17%	83%	69110	13%	87%	61474	13%	87%	60252	8%	92%	32747
A	Z	50A03754	86%	14%	26369	149%	-49%	46096	128%	-28%	39040	119%	-19%	36041	27%	73%	13076	34%	66%	10656
A	Y	2501222	37%	63%	29018	22%	78%	15099	164%	-64%	138198	61%	39%	56273	42%	58%	33996	14%	86%	10969
A	X	54280051	49%	51%	186067	40%	60%	151619	42%	58%	145040	38%	62%	145158	38%	62%	128595	23%	77%	87735
A	Y	53593038	38%	62%	202311	30%	70%	158117	21%	79%	131763	33%	67%	157660	75%	25%	326473	14%	86%	75029
A	X	51382071	58%	42%	173461	30%	70%	77518	39%	61%	96513	25%	75%	72504	42%	58%	116264	17%	83%	51758
A	X	53130352	24%	76%	98056	15%	85%	56274	12%	88%	48413	17%	83%	64794	17%	83%	67586	8%	92%	31240
A	Y	51381022	31%	69%	123634	32%	68%	102266	39%	61%	121564	31%	69%	99000	27%	73%	92923	11%	89%	40693
B	Z	50A02398	NA	NA	658	NA	NA	2770	NA	NA	6116	NA	NA	1862	NA	NA	1652	NA	NA	1546
B	Z	54053050	36%	64%	3026	37%	63%	2528	21%	79%	1604	40%	60%	2891	34%	66%	3233	15%	85%	1190
B	Z	50507158	NA	NA	4687	NA	NA	4991	NA	NA	5655	NA	NA	4589	NA	NA	6752	NA	NA	3238
B	Y	50A20221	153%	-53%	9010	75%	25%	4729	62%	38%	4693	68%	32%	4541	50%	50%	4138	41%	59%	2849
B	Y	S048194	49%	51%	1678	173%	-73%	3428	177%	-77%	3220	140%	-40%	2705	173%	-73%	3177	25%	75%	763
B	Z	54280955	NA	NA	7807	NA	NA	11015	NA	NA	10666	NA	NA	11341	NA	NA	7687	NA	NA	9882
B	Z	50A61091R	NA	NA	6602	NA	NA	6666	NA	NA	3799	NA	NA	6445	NA	NA	8188	NA	NA	4123
B	Y	50T11364	56%	44%	5833	38%	62%	4313	36%	64%	4280	32%	68%	3418	50%	50%	5779	19%	81%	1926
B	Y	52731016	141%	-41%	2639	545%	-445%	5178	548%	-448%	4838	331%	-231%	3489	277%	-177%	3198	79%	21%	1315
B	Y	2500507	65%	35%	2986	38%	62%	2231	29%	71%	1837	27%	73%	1838	25%	75%	1841	22%	78%	1099
B	Z	2405829-2	NA	NA	7374	NA	NA	4424	NA	NA	5553	NA	NA	5943	NA	NA	5099	NA	NA	6137
B	Z	2500638	40%	60%	3761	42%	58%	4808	43%	57%	5142	30%	70%	3351	57%	43%	6642	25%	75%	3001
B	Y	54056452	108%	-8%	2920	290%	-190%	3885	299%	-199%	3774	130%	-30%	2660	191%	-91%	2993	63%	37%	1307
B	Z	54296077	NA	NA	3581	NA	NA	3697	NA	NA	3628	NA	NA	2763	NA	NA	2560	NA	NA	2572
B	Z	53110111	112%	-12%	22643	60%	40%	16894	69%	31%	19066	35%	65%	10666	59%	41%	20196	22%	78%	6933
B	Y	2500226	32%	68%	1943	31%	69%	1970	22%	78%	1337	28%	72%	1765	62%	38%	2909	21%	79%	1245
B	Z	50370945	29%	71%	1436	30%	70%	1431	101%	-1%	3287	32%	68%	1712	47%	53%	2251	32%	68%	2060
B	Z	53592441	NA	NA	17801	NA	NA	11051	NA	NA	10722	NA	NA	10451	NA	NA	7465	NA	NA	9973
B	Z	52731132	NA	NA	0	NA	NA	0	NA	NA	10074	NA	NA	674	NA	NA	41	NA	NA	8016
B	Y	54050494	41%	59%	2200	188%	-88%	3559	291%	-191%	3636	142%	-42%	3278	139%	-39%	2842	25%	75%	1374
C	Z	50A64226R	NA	NA	0	NA	NA	1727	NA	NA	1252	NA	NA	1437	NA	NA	786	NA	NA	645
C	Z	MATRIX OP5	NA	NA	6243	NA	NA	4792	NA	NA	4853	NA	NA	4701	NA	NA	19692	NA	NA	4288
C	Z	2501671	NA	NA	633	NA	NA	964	NA	NA	1048	NA	NA	918	NA	NA	1036	NA	NA	752
C	Z	50384720	48%	52%	365	58%	42%	527	53%	47%	547	60%	40%	528	104%	-4%	783	22%	78%	233
C	Y	50359863	NA	NA	360	NA	NA	348	NA	NA	534	NA	NA	271	NA	NA	341	NA	NA	254
C	Z	50A30072R	60%	40%	411	93%	7%	426	129%	-29%	569	76%	24%	352	35%	65%	229	17%	83%	171
C	Z	50A36029	NA	NA	567	NA	NA	368	NA	NA	577	NA	NA	459	NA	NA	309	NA	NA	502
C	Z	50369774R	NA	NA	292	NA	NA	486	NA	NA	533	NA	NA	540	NA	NA	813	NA	NA	552
C	Z	5K00A352	NA	NA	3575	NA	NA	2223	NA	NA	2458	NA	NA	2262	NA	NA	2353	NA	NA	1986
C	Z	53455313	NA	NA	709	NA	NA	683	NA	NA	548	NA	NA	490	NA	NA	556	NA	NA	360
C	Z	50A47394	NA	NA	636	NA	NA	764	NA	NA	1130	NA	NA	866	NA	NA	903	NA	NA	702
C	Y	53412045	88%	12%	1285	37%	63%	868	27%	73%	776	31%	69%	749	69%	31%	1163	33%	67%	505
C	Z	50T36971	56%	44%	1070	46%	54%	690	39%	61%	762	61%	39%	774	55%	45%	1082	21%	79%	452
C	X	57351941	23%	77%	230	17%	83%	166	17%	83%	162	14%	86%	144	13%	87%	118	9%	91%	87
C	Z	56340082	NA	NA	0	NA	NA	400	NA	NA	802	NA	NA	111	NA	NA	84	NA	NA	589
C	X	53410977	50%	50%	474	35%	65%	311	27%	73%	250	37%	63%	320	42%	58%	391	15%	85%	144
C	X	50A19826	82%	18%	351	119%	-19%	392	135%	-35%	456	90%	10%	317	115%	-15%	409	36%	64%	150
C	Z	50366174	NA	NA	651	NA	NA	919	NA	NA	1067	NA	NA	810	NA	NA	435	NA	NA	921
C	Z	50339631	NA	NA	798	NA	NA	682	NA	NA	726	NA	NA	637	NA	NA	558	NA	NA	583
C	Z	50A72702R	NA	NA	1084	NA	NA	1850	NA	NA	1300	NA	NA	1947	NA	NA	269	NA	NA	295

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In contrast, Croston's method behaved similarly to classical exponential smoothing for items whose time series was continuous, and the β parameter had minimal effect on the accuracy of the results in these cases. For example, the item 53591776 (AX) in Table 2 exhibited very stable behaviour, with optimal values of α and β of 0.575 and 0.1, respectively, and a resulting MAPE error of 11%. Compared to the previous methods, in this case, Croston's method offered approximately comparable accuracy, with the advantage of higher robustness to possible zero values in the demand time series. In contrast, for the item 51381043 (AZ), which is characterized by high volatility, Croston's method produced a prediction that is practically applicable and does not exhibit negative DPA. The increased reactivity of the model drives this result - using values of $\alpha = 0.975$ and $\beta = 0.1$ managed to compress the MAE to 19.791, compared to 96.617 for the simple linear regression.
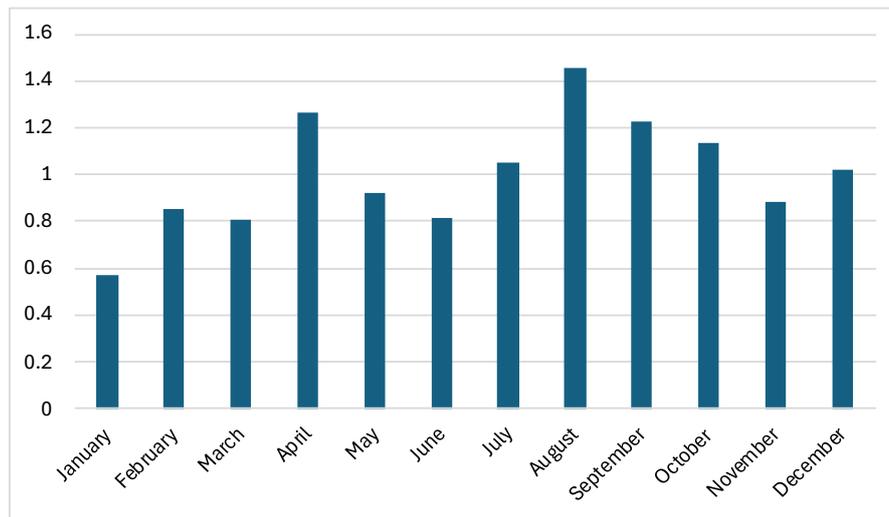
Figure 1 Average seasonal indices

Croston's method proved highly suitable for handling discontinuous and irregular time series, especially for items falling into the AY, BZ and CZ categories, where traditional prediction models – such as linear regression or moving averages – failed or provided irrelevant results. An important contribution of this method is its ability to ignore nulls while smoothing the magnitude and frequency of demand separately. This significantly improves prediction accuracy, where conventional methods fail to respond adequately to the fluctuations or irregularly recurring nature of demand.

It should be added, however, that despite the generally positive results, there were a few exceptions where Croston's method did not provide a significant improvement. This was mainly the case for items whose nature was closer to continuous or periodic consumption - in these cases, the model de facto converged to the results of classical exponential smoothing, while the parameter β did not have a significant impact on the result here. In these situations, it was found that other methods (e.g. linear regression with indices) could offer similar or even higher accuracy with less computational effort.

The bootstrap method, the principle of which was explained in Chapter 2, provides an alternative approach to quantifying demand uncertainty through repeated random sampling of historical values. Although it does not directly predict future values, it allows for estimating the likely range of future demand and identifying variability across items.

The process of generating the simulations was implemented in MS Excel through a function (16).

$$=INDEX(\$B\$2:\$B\$28;RANDBETWEEN(1;COUNT2(\$B\$2:\$B\$28))) \quad (16)$$

This formula combines the INDEX, RANDBETWEEN, and COUNT2 functions. The COUNT2 function determines the number of non-empty cells in the input series (in this case, the demand observations). RANDBETWEEN randomly generates an integer between 1 and that number, and INDEX returns a value at the corresponding position. This procedure creates a new simulated sample that respects the original empirical distribution. The mean and quantiles (5th and 95th percentiles) were then calculated from each simulation generated, producing a confidence interval representing the likely range of future demand. For example, for 53591776 (AX), the average simulated demand ranged between 1.7 and 1.8 million. CZK with a relatively narrow range from 788,473 CZK (5% quantile) to 2,526,740 CZK (95% quantile), indicating relatively stable and predictable behaviour, see Figure 2. The use of this approach, therefore, provides important context for future supply decisions, especially when building insurance stocks or planning a purchasing strategy.

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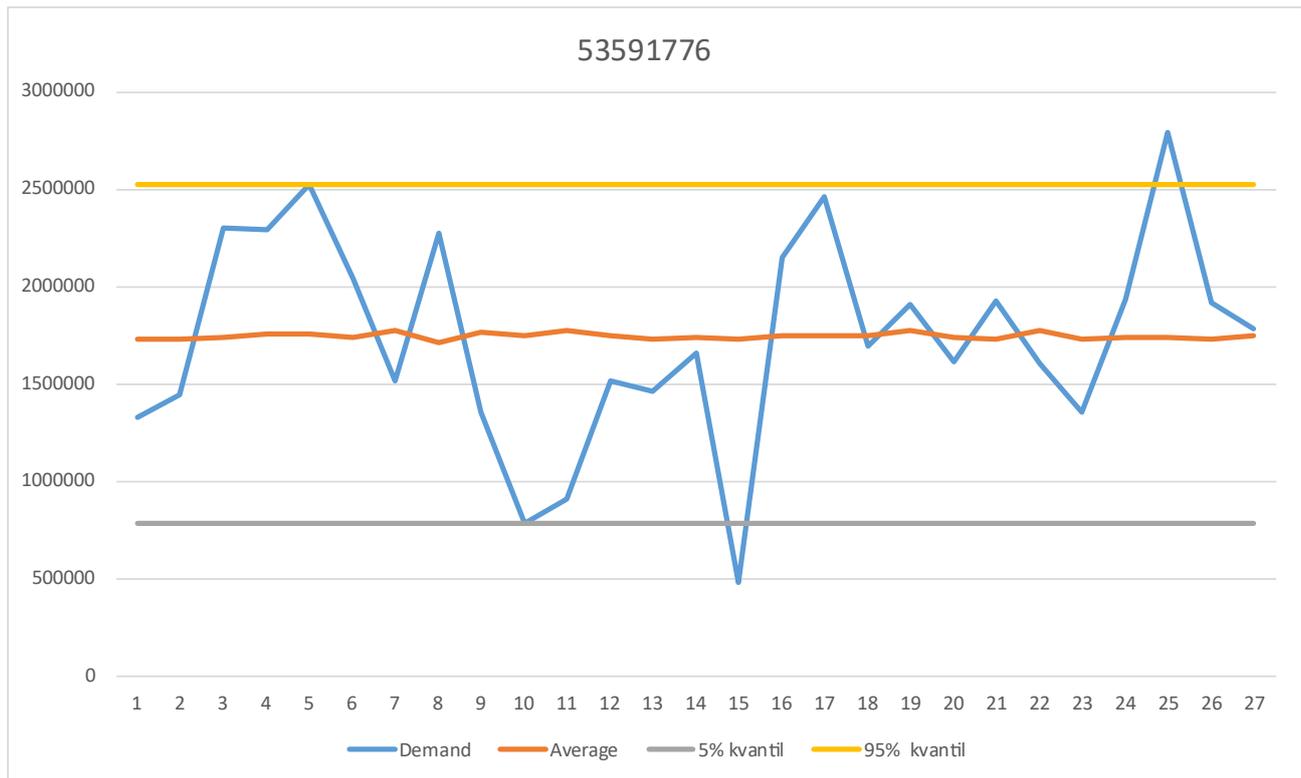
Figure 2 Simulated stock item demand 53591776

5   Results and discussion

Based on the analyses, the following procedure can be recommended for demand (consumption) forecasting. The first step is an ABC analysis, which divides the stock assortment into three basic groups according to the selected indicator. Group A should be given the greatest attention in inventory management, and the most accurate prediction of stock levels should be sought. On the other hand, for groups B and C, it may be acceptable to use simpler prediction methods. The second step is to carry out an XYZ analysis to identify fluctuations in demand or consumption. For items in categories Y and Z, looking for the causes of fluctuations is necessary. Therefore, it may be recommended to calculate seasonal indices, which can be used to determine whether seasonality or other causes or randomness are behind the fluctuations in demand.

Based on the ABC/XYZ classifications, a specific prediction method can be recommended for each group of items, considering the stability of demand, its variability and the item's importance. For the AX group of items characterized by high stability and often trend behaviour, linear regression or moving average with a shorter period (10) may be recommended. Croston's method for this group has frequently provided results comparable to simpler methods. It can therefore be regarded as unnecessarily demanding for this group of stocks. Alternatively, a simple exponential smoothing may be recommended instead of Croston's method, as there are virtually no periods of zero demand in the time series for the AX group.

Group AY included items with regular but more volatile demand. If seasonality is the cause of the fluctuations, a linear regression supplemented with seasonal indices may be well recommended. If the causes of volatility differ, Croston's method proved to be the only reliable method in specific cases, with an extremely high reactivity setting (α approaching 1.0), because demand, although not intermittent, was highly volatile and difficult to predict.

The analysis showed that Croston's method, which was initially designed typically for series with sporadic demand (group Z), proved to be successful in optimizing the parameters α and β (0.1-1.0) for other groups as well. In the BY group, Croston's method often showed more reliable prediction results than moving averages or linear regression. This result is particularly accurate for time series with occasional demand shortfalls. In this group, Croston's method performed best when the parameter α was set in the range 0.1-0.6, when it was able to smooth the slightly discontinuous series effectively.

Croston's method was often the only applicable method in the AZ and BZ groups, where outages were frequent and predictability was very difficult. For items in category C with low demand values, the naive method can be considered in terms of application difficulty or simplicity. The recommendations are summarised in Table 3.

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Table 3 Recommendations for individual methods for demand forecasting

	X	Y	Z
A	Linear regression Moving averages (10) Exponential smoothing	Linear regression plus seasonal indices Croston's method	Croston's method
B	Linear regression Moving averages (10) Exponential smoothing	Croston's method	Croston's method
C	Naive forecasting Croston's method	Naive forecasting Croston's method	Naive forecasting Croston's method

For key inventory items (Group A), we also recommend supplementing traditional forecasting algorithms with a bootstrap method for estimating uncertainty and setting service levels, allowing the company to manage its insurance inventory better and prepare for fluctuations in demand.

Based on the research results, it was recommended that the company implement a predictive inventory management system and integrate it into the Power BI environment, with a potential connection to an existing ERP system. This system would automate planning and, at the same time, reduce decision risk in purchasing and production. In conclusion, it must be emphasized that the selection of a prediction method cannot be done in a completely universal way – for each item, an appropriate model should be individually selected, taking into account not only the type of time series, but also its turnover, importance in the supply chain and impact on the company's operational activities. This approach can ensure that the prediction is simple in application and practical in day-to-day decision-making.

6   Conclusions

The main contributions of the article can be divided into two areas. The first area is research and practical application. As part of the research, an easy-to-apply methodology was proposed for predicting individual inventory items based on their importance and fluctuations in demand or consumption. This methodology was verified using real data from a custom manufacturing company. The second benefit is educational. The proposed methodology can be used to teach inventory management in subjects such as logistics or operations research.

The research proposed a methodological procedure for forecasting and inventory management for specific assortment items concerning their variability, significance and demand occurrence over time. The solution included both data preparation and classification of items using ABC/XYZ methods, as well as the application and evaluation of six prediction methods based on real data from the company.

The chosen approach allowed a detailed assessment of the behaviour of individual items. It also provided a practical tool to approach the selection of a prediction method systematically. It was found that the accuracy of the different methods varies significantly depending on the type of time series. Within the ABC/XYZ classifications, groups of items were identified for which a particular method repeatedly performed well (e.g. Croston's method for categories Y or Z and linear regression and moving average for category X). The results confirm that no method is universally applicable. For successful prediction, knowledge of item behaviour must be combined with an appropriate analytical technique. To understand the demand behaviour of inventory items, we recommend using a bootstrap simulation, which is relatively easy to apply. Bootstrap simulation provides essential information about demand uncertainty and allows the creation of predictive scenarios. The article offers practical instructions on how to perform such a simulation in MS Excel.

Three metrics – MAE, MAPE and DPA – were used to evaluate the methods, with the outputs compiled into clear tables and graphs. Particular attention was paid to Croston's method, for which the α and β parameters were optimized by grid search.

The results are limited by the nature of the data and the corporate environment of custom manufacturing with irregular demand. The analysis was also affected by the computational constraints of optimizing the parameters of Croston's method and performing bootstrap simulations in MS Excel and VBA, where a trade-off between computational finesse and time was required. Another limitation was the incompleteness of the input data.

The main contribution of the research was the development of a repeatable and adaptable demand forecasting procedure that considers the series' variability and the items' importance. The proposed system allows both the selection of the correct forecasting model and the quantification of risk and uncertainty, which is essential for decision-making in inventory planning. Last but not least, the research provides a basis for the possible integration of predictive logic into the business environment, either in the form of Power BI tools or as a basic output for an ERP system.

From a practical point of view, it can be recommended that each company should base its inventory management not only on historical data, but also on the nature and importance of individual items. Combining ABC/XYZ classifications with testing methods based on their performance under given conditions has proven to be a workable framework that can serve as a model for other manufacturing companies with similar demand characteristics.

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Electric vehicles for cleaner urban logistics: what motivates consumers to choose green delivery?
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Electric vehicles for cleaner urban logistics: what motivates consumers to choose green delivery?

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Keywords: behavioral intention, electric vehicles, last-mile logistics, sustainable development.
Abstract: The rapid expansion of e-commerce has intensified pressures on urban logistics and last-mile logistics flows. This study examines psychological drivers of consumers' intention to select electric vehicle based last-mile logistics within a green logistics flow perspective, integrating the Value-Belief-Norm and Theory of Planned Behavior frameworks. We explicitly frame the problem as reducing the environmental burden of material, information, and financial flows in the last mile while maintaining service quality; the goal is to identify value- and norm-based antecedents that strengthen intentions to choose electric vehicle delivery services. Using a structured survey (n = 618) and PLS-SEM, results show altruistic and biospheric values shape ecological worldviews, which activate perceived adverse consequences and ascription of responsibility, forming pro-environmental personal norms that raise attitude, subjective norms, and perceived behavioral control, thereby increasing behavioral intention toward electric vehicle delivery. This study contributes by theorizing electric vehicle (EV) adoption as a green logistics flow decision rather than a matter of personal mobility, integrating value-to-norm pathways with the flow management requirements of last-mile logistics operations, and proposing actionable strategies for logistics providers to design value-aligned nudges and communicate flow efficiency with lower emissions.

1 Introduction

The boom in Vietnam's e-commerce market in 2023 has created immense pressure on urban logistic sector, particularly last-mile logistics services which primarily rely on gasoline-powered motorcycles in both urban and rural areas in Vietnam - an easy to use, flexible, and cheap method for [1] This is because they are easy to use, flexible, and cheap. They are also used for last-mile logistics services. However, in 2015, more than 40% of greenhouse gas emissions from transportation were attributed to the delivery process [2]. In response to this and the growing trend toward green logistics, in July 2025, the Vietnamese government announced a major policy to phase out gasoline-powered motorcycles in central Hanoi by July 2026, with full enforcement across larger metropolitan zones by 2030. This legislative move, aimed at addressing severe urban air pollution and accelerating the national net-zero roadmap, signals a radical transition toward electric mobility. As a result, the adoption of electric vehicles in Vietnam has risen at a recognizable level. The two-wheeler market, traditionally dominated by internal combustion engine vehicles, is witnessing a significant rise in electric two-wheeler adoption revealing that the market share of electric two-wheelers rose from 4.9% in 2019 to 8.3% in 2020 [3]. A prime example of this transition is Xanh SM, a Vingroup subsidiary. By deploying a massive fleet of electric vehicles for both ride-hailing and its dedicated last-mile logistics service, Xanh SM Express, the company is actively pioneering sustainable logistics solutions in Vietnam. However, while general consumer preferences for sustainability are well-documented, the specific decision-making dynamics behind the adoption of electric vehicle-based delivery services in the Vietnamese context remain under-explored. Though interest in sustainable logistics has expanded among scholars and policymakers, a significant research void persists regarding the behavioral factors that influence consumers'

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willingness to accept electric vehicle last-mile logistics services. This gap is especially in emerging markets like Vietnam, where rapid e-commerce growth creates new delivery challenges and opportunities. Current literature primarily emphasizes the technological efficiency, cost-effectiveness, and environmental benefits of electric vehicle fleets [3] while also paying attention to the cognitive, emotional, and social drivers that ultimately determine whether consumers adopt these greener logistics options. Most existing research focuses on electric vehicle adoption for personal travel, leaving a noticeable gap regarding commercial delivery fleets in fast-growing cities worldwide [4]. Recent scholars have urged investigators to blend value-oriented theories with intention models to illuminate how consumers choose greener logistics [5]. This paper addresses these problems by testing a joint Value-belief-norm theory and the Theory of planned behavior framework to examine ecological values, awareness of harm, and perceived control influence consumers to adopt electric vehicle-powered delivery. In doing so, it adds empirical evidence linking psychological drivers to sustainable innovation in commercial logistics.

Acknowledging the limited research on last-mile logistics services using electric vehicles, this study evaluates respondents' perspectives on the values, beliefs, and norms that shape their attitudes toward last-mile logistics. It analyzes the key determinants that affect consumer choices for Xanh SM including electric vehicles during the last-mile logistics stage. The rest of this article is structured as follows. Section two reviews the relevant literature on last-mile logistics, the adoption of electric vehicles in sustainable logistics, and the theoretical underpinnings of the VBN and TPB. Section three describes the research methodology, including measurement development, data collection, and analytical procedures. Section four presents the empirical findings from the PLS-SEM analysis, including descriptive statistics, measurement model assessment, and hypothesis testing then discussing the main conclusions, theoretical contributions, and practical implications while also highlighting the study's limitations and directions for future research.

2 Literature review
2.1 Last-mile logistics
In B2C e-commerce, the last mile is regarded as the last segment of supply chains when parcels are delivered to a specific delivery location or the recipient's residence (doorstep). Last-mile logistics is currently regarded as one of the most important, costly, and inefficient flow management and operations of the e-commerce environment. The rapid expansion of e-commerce and customer demand for fast shipping has significantly escalated last-mile transportation, especially for residential deliveries [6].

2.2 Electric vehicle in sustainable trends
Electric vehicles have emerged as a critical enabler of sustainable mobility, offering a promising solution to reduce greenhouse gas emissions and mitigate the environmental impact of fossil fuel-based transportation [7]. Their lower life-cycle emissions and potential for energy diversification align with global de-carbonization targets and the pursuit of net-zero emissions by mid-century [7]. In the last-mile logistics sector, electric vehicles help both the planet and the budget by removing tailpipe pollution from city streets and by working well with telematics, real-time tracking, and smart routing software. Fresh research shows that, when tied to solar or wind recharging, electric delivery vans cut greenhouse gases, silence diesel engines, boost local energy security, and support circular-economy goals [7]. Better batteries and steady wireless links are also speeding the roll-out of electric vehicle fleets in crowded urban centers where final-leg emissions worsen asthma and heart disease [7]. Together, these trends point to a turning point in logistics, shifting firms from carbon-heavy practices to greener, tech-savvy flow management and operations.

2.3 Value-belief-norm theory
In 2000, Stern developed the Value-Belief-Norm theory by expanding the norm activation theory, which has been established to investigate altruistic purposes and behaviors in the same context to better illuminate pro-environmental behaviors and attitudes by incorporating essential value concepts. The Value-belief-norm theory examines how pro-environmental personal norms are formed through a progressive mechanism, beginning with environmental values, followed by an awareness of the consequences, and the ascription of responsibility, which collectively contribute to shaping personal environmental intentions and actual behaviors [8]. Later, as confirmed by [9], the value orientations were further categorized into altruistic values, biospheric values, and electric vehicles. First, an altruistic value orientation clearly shows that people care about the welfare of other humans. Recent updates to Schwartz's Norm Activation Model (1997) describe how each person gradually builds a unique moral standard, a private sense of obligation that feels binding. When they think serious harm is likely, that internal rule pushes them to act, often with little cost-benefit weighing attached. Second, a biospheric value frame broadens the idea of personal norms by making nature, the planet, and all non-human life part of the moral community, allowing altruistic instincts to extend into environmental cases. Third, an egoistic view centers on self-interest; when green actions appear too costly, it can freeze or derail even well-meaning citizens. This study, grounded in the Value-belief-norm model, asks how those three orientations-altruistic, biospheric, and egoistic-shape awareness of outcomes, feelings of responsibility, and the growth of personal normative pressure. To

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answer, we combine Value-belief-norm with the Theory of planned behavior and track whether people adopt new, cleaner technologies electric last-mile logistics vehicles-particularly in urban zones-when they see those choices aligned with their respective value profiles.

2.4 Theory of planned behavior

The Theory of Planned Behavior offers a useful mini framework that breaks down human choice into three clear parts: attitude toward the behavior gauges whether a person broadly approves or disapproves of a specific act, subjective norms capture the social signals, from friends or headlines, that nudge someone closer or further away from that act, and perceived behavioral control reflects the confidence or doubt a person feels about carrying the act out when the moment arrives. When combined, attitude toward the behavior, subjective norms, and perceived behavioral control jointly signal the strength of a person's intention to behave in a certain way, a point underscored in recent work by Lee description of responsibility colleagues (2023) [10]. Core beliefs, of course, form the filter through which every technological promise must pass: they quicken or slow the response long before a gadget ever lands on a kitchen counter. Turning electric vehicles into the backbone of last-mile logistics therefore entails more than swapping batteries for diesel; it means revising a logistics playbook generations have relied upon [10]. Moreover, for many companies, the choice to use electric vehicles for the final stage of shipping has become a visible commitment to sustainability.

Consumer decisions are commonly influenced by outside initiatives, such as educational protests and metropolitan green movements, and by inward beliefs, like seeing oneself as a green shopper [11]. To turn a sporadic choice into routine behavior, consumers need more than prompts; they must also possess convictions that push them to keep going [11]. Because electric vehicles could fundamentally change how goods move through neighborhoods and how residents commute, combining the Value-belief-norm theory with the Theory of planned behavior offers a fuller map of the mental journey that ends in a purchase. Both frameworks show that underlying beliefs and cherished values can lead people to buy-or keep them from doing so. Pinpointing that link matters to Xanh SM as it aims to link its electric vehicles to daily green habits and help solve urgent last-mile logistics issues.

2.5 Hypothesis development

According to the Value-belief-norm theory, egoistic, altruistic, and biospheric value orientations are the three main components that impact pro-environmental behavior [12]. In the context of green transportation, an egoistic value is a symbol of personal happiness, which reflects a family's or individual's desire for a clean and healthy home environment. Egoistic values encourage people to conserve aspects of the environment that affect them. For example, individual health satisfaction, such as good health or a higher quality of life, may motivate people to behave environmentally. This idea has been reconfirmed by a study by Gansser and Reich (2023) [13], who also argue that the more egoistic environmental concerns are advanced, the more environmentally sustainable behavior regarding the environment and climate will be led. While egoistic values consider self or family concerns, altruistic values refer to personal decision-making when a person is conscious of the consequences of their action and individually responsible for others [14]. The more a person is aware of the consequences of their decision, the more likely they are to exhibit self-sacrificing behavior [14]. Altruistic values are rudimentary for influencing consumer environmental behavior [14] and increasing the effort to provide a cleaner solution for environmental problems, energy conservation, and recycling. altruistic value positively promotes more environmental awareness among consumers. Biospheric values play another key role in value models when it encompasses environmental behavior and reveals how alternative values influence pro-environmental actions [14]. Biospheric values have already been a significant concern for ecologists and environmentalists. It is clarified as the energy and resources required to sustain Earth's activities, including human economic activities [14]. Human environmental concern is increasing as people become increasingly aware of unsustainable consumption forms, which lead to serious environmental issues, such as disastrous pollution, climate change, and global warming [13]. Due to the increasing consumer environmental concern driven by egoistic values, altruistic values, and biospheric values, as evidenced above, the following hypotheses are formulated:

H1: Egoistic values positively influence ecological worldview.
H2: Altruistic values have a positive influence on the ecological.
H3: Biospheric values positively influence ecological worldview.

People with a high ecological worldview tend to make choices that are better for the environment, like buying electric cars as part of their sustainable lifestyle [15]. They believe electric cars are a cleaner, more sustainable option than those that run on fossil fuels, as they aim to reduce air pollution, greenhouse gas emissions, and fossil fuel use [16]. Using electric vehicles for last-mile logistics highlights the environmental impact of excessive resource consumption, which is detrimental to the environment. Consumers who care a lot about the environment want to meet their needs more quickly and easily with electric vehicles without having a direct effect on the environment [12].

H4: Ecological worldview has a positive influence on perceived adverse consequences for valued objects.

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Adverse consequences for valued objects explain how people become concerned about the harm their choices can cause to things they care about once they grasp the link between their behavior and that harm [9]. From this perspective, norm activation is the mental switch that occurs when individuals recognize the links, accept responsibility for the damage caused by agencies, and take a particular pro-environmental action. When a consumer realizes, for instance, that ordering rides that rely on petrol cars makes the planet worse, they often feel compelled to explore greener alternatives [17]. Substituting that ride with an electric scooter or e-bike then appears less like an optional upgrade and more like a minor but essential act toward cleaner air and smaller carbon counts, a belief shared by many last-mile users today [11]. For this reason, we advance the following hypothesis:

H5: Adverse consequences for valued objects positively influence the perceived ascription of responsibility.

The ascription of responsibility ascription of responsibility refers to the degree to which individuals believe they share blame for environmental degradation and its consequences. According to the Norm Activation Model, personal pro-environmental norms pro-environmental personal norms emerge from internalized values, perceived moral duties, and self-imposed expectations to act in ways that safeguard nature [18]. Different contexts have shown a consistent positive link between ascription of responsibility and pro-environmental personal norms. He & Zhan (2018) argued that people form stronger personal norms in favor of electric vehicles, electric vehicle adoption, and related services once they acknowledge their environmental accountability [19]. Consequently, ascription of responsibility can shape intentions to shift toward electric or hybrid vehicles [10]. The following hypotheses are proposed:

H6: Ascription of responsibility positively influences perceived pro-environmental personal norms.

Personal or moral norms are self-expectations, obligations, and punishments rooted in internalized values. In general, behavioral contexts, people may purchase green items due to both hedonic motivation and obligation-based individual standards. Pro-environmental personal norms shape an individual's moral responsibility to mitigate harmful impacts and support cleaner practices [20]. Positive attitudes toward electric vehicle adoption emerge when it is seen as desirable or socially acceptable [10]. Empirical evidence from other studies has shown that personal norms influence pro-environmental behavior. In this study, we assume that:

H7: Pro-environmental personal norms positively influence attitude toward the behavior.

Personal norms encourage subjective norms by fostering an environment where sustainable practices are morally valued and socially accepted as cleaner alternatives. In general behaviors, pro-environmental personal norms impact subjective norms through social modeling and the promotion of eco-friendly practices. People's sense of social responsibility for environmental issues strengthens when personal norms align with societal pressure to adopt eco-friendly lifestyles. For last-mile logistics using electric vehicles, Haustein and Jensen (2018) argued that subjective norms are shaped by personal norms, which influence vehicle choice [21]. Additionally, Niu et al. (2023) demonstrate that pro-environmental behaviors can influence others' actions [22], supporting a specific hypothesis:

H8: Pro-environmental personal norms positively influence subjective norms.

Lee et al. (2023) suggest that a connection exists between pro-environmental personal norms and perceived behavioral control [10]. Niu et al. (2023) note that people's norms regarding environmentally friendly behavior can encourage them to adopt practices that protect the environment [22]. Some authors suggest that people are more likely to adopt eco-friendly and cleaner habits when they have strong personal norms that support environmental conservation. Based on the evidence, we suggest the following hypothesis:

H9: Pro-environmental personal norms positively influence perceived behavioral control.

Attitude-the degree to which a person views an action or a behavior favorably or unfavorably is a key driver of intention in behavioral research because it pushes people to act [23]. Generally speaking, individuals commit to a behavior when they believe that the outcome will benefit them personally [23]. Convenience, speed, and dependability steadily encourage consumers to use delivery platforms regularly, for instance, when those elements are promised and delivered [24]. Electric vehicle fleets add a distinctive layer to this puzzle: their low emissions, modern interfaces, and even novel sound profiles often heighten positive expectations and amplify favorable attitudes. Building on that evidence, we propose the following hypothesis:

H10: Attitude toward the behavior positively influences behavioral intention in applying electric vehicles.

Subjective the perception of approval or disapproval from relevant others - has a robust influence on individuals' behavioral intention [25]. People tend to adopt a course of action when they believe respected reference groups visibly endorse it [26]. Similarly, consumers display greater compliance with green initiatives when firms visibly pivot toward sustainable flow management and operations [26]. Offering eco-preferable delivery modes not only reinforces these

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norms but also safeguards a positive standing with environmentally aware stakeholders [26]. In this study, we assume that:

H11: Subjective norms positively influence behavioral intention.

Perceived behavioral control refers to the belief that an individual can perform a specific action. It has a significant impact on how consumers perceive behavioral intention As the trend toward sustainability grows, people's beliefs in their ability to make a difference and the support they receive from others for green practices, such as government incentives or widespread electric vehicle adoption, make perceived behavioral control even stronger [27]. Based on what we found, we came up with the following hypothesis:

H12: Perceived behavioral control positively influences behavioral intention.

Figure 1 illustrates the proposed research model, which integrates the Value-belief-norm theory and the Theory of Planned Behavior.
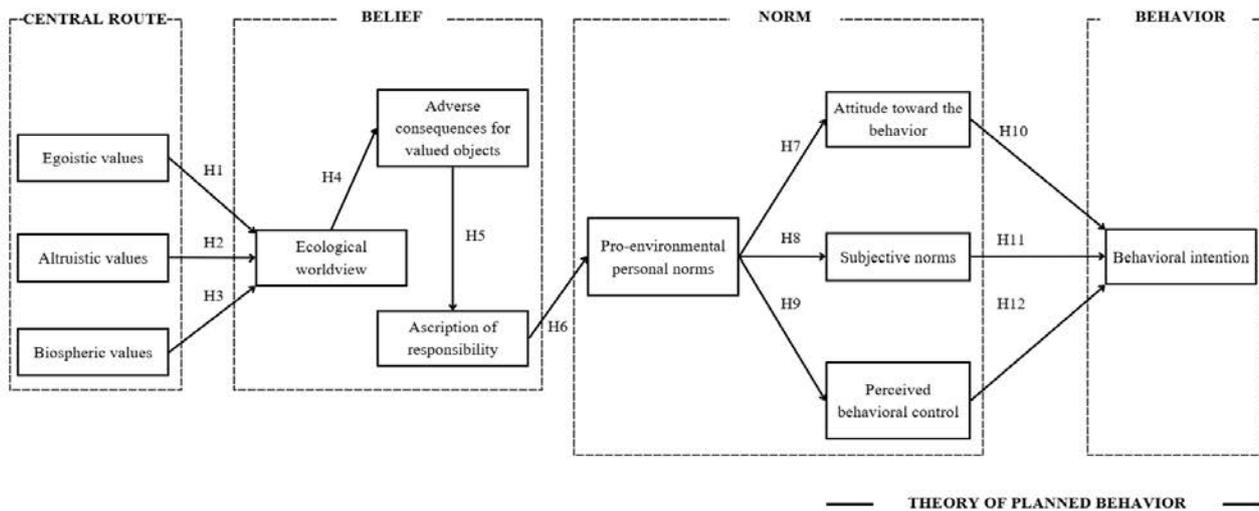
Figure 1 Proposed model

3 Methodology
3.1 Measurement scale and survey development

Following an extensive literature review, a questionnaire was constructed specifically for this study. Likert-type scales with seven points are employed for measurements for all items ranging from 'strongly disagree' to 'strongly agree.' All items used in the measurement are based on pre-existing scales and well-established and reliable instruments. Some measurement items were chosen from authorized sources for the comprehensive software assessment. For egoistic, altruistic, and biospheric values, four items have been selected for each variable [28]. For the ecological worldview, three items have been chosen for each variable [29]; adverse consequences for valued objects and ascription of responsibility [30]. Four items have also been selected for assessing pro-environmental personal norms and attitudes toward the behavior [30]. Lastly, to assess subjective norms, perceived behavioral control, and behavioral intention, three items have been identified for each variable [10].

3.2 Sampling and data collection

After minor adjustments, the close-ended survey, conducted through the Google Forms platform, targets participants from diverse age groups. The survey has two main sections. Demographic data about the respondents were included in the first section of the survey, and related measurement items were included in the second section. (Appendix A). Survey forms are distributed to participants via various Facebook Groups. Data collection occurred from September to December 2024. A total of 630 responses were collected during the study period, and 618 legitimate samples were used in the subsequent analysis. The sample size collected in this study meets the statistical requirements for an empirical study.

3.3 Data analysis

Using PLS-SEM with SmartPLS 3, the measurement and structural models were assessed to validate the hypotheses. Since our measurement model is built with reflective latent factors, it is crucial to evaluate and fulfill specific criteria, including the significance of outer loadings of each observation variable, reliability, composite reliability, average

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variance extracted, and discriminant validity. Our research model will be tested for the structural model to confirm the suitableness of several key criteria, e.g., collinearity between variables, the significance of main path coefficients, R^2. Data analysis was performed using SmartPLS 3 to ensure precision and comprehensive results.

4   Results and discussion
4.1   Descriptive characteristics of the sample
   Table 1 presents the demographic characteristics of the 618 respondents who participated in this study and provided valid data. In terms of gender, 60.4% of the participants were female, while 39.6% were male, indicating a slight female dominance in the sample. Concerning age, most respondents were between 26 and 35 years old (41%), followed by those aged 36-45 (20%),   16-25 (17.8%), and 46-55 (14.3%). Only 6.9% were above 55 years of age, suggesting that the majority of the sample was concentrated in the working-age population under 45 years old. In terms of monthly income, the most significant proportion of respondents (42.3%) reported earning between 10 and 15 million VND, followed by 21.1% earning below 5 million VND, and 20.1% earning between 5 and 10 million VND. A smaller portion of participants earned from 15 to 20 million VND (12%) and above 20 million VND (4.5%), reflecting a modest income distribution across the sample. Regarding education level, the majority (58%) held an undergraduate degree, while 25.1% had completed high school or lower education. Additionally, 16.9% of respondents obtained a postgraduate degree. This suggests that most participants were relatively well-educated, with over 70% holding a university-level education or higher.

Table 1 Descriptive characteristics of the sample

	Profile	Frequency N=618	Percentage 100%
Gender	Male	245	39.6%
	Female	373	60.4%
Age	16 - 25	110	17.8%
	26 - 35	254	41%
	36 - 45	123	20%
	46 - 55	88	14.3%
	Above 55	43	6.9%
Income Per Month	Below 5 million VND	130	21.1%
	From 5 million VND to 10 million VND	124	20.1%
	From 10 million VND - 15 million VND	261	42.3%
	From 15 million VND - 20 million VND	74	12%
	Above 20 million VND	29	4.5%
Education level	High school or below	155	25.1%
	Undergraduate level	358	58%
	Postgraduate level	105	16.9%

4.2   Measurement model
   The measurement model's discriminant validity, convergent validity, and reliability have all been calculated (Table 2). The outer loading values of all observation items are above 0.708, indicating that these variables have contributed significantly to the corresponding factor. Regarding reliability, the composite reliability value and Cronbach's alpha value for every item exceeded 0.7, indicating good reliability. The average variance extracted values exceed 0.5, indicating strong convergent validity.

Table 2 Reliability and convergent validity assessment

Variables	Items	Outer loadings	Cronbach's alpha	Composite Reliability	AVE
Egoistic values	EV1	0.870	0.883	0.919	0.739
	EV2	0.857			
	EV3	0.847			
	EV4	0.866			
Altruistic values	AV1	0.850	0.875	0.915	0.729
	AV2	0.899			
	AV3	0.821			
	AV4	0.844			
Biospheric values	BV1	0.876	0.896	0.927	0.764
	BV2	0.859			
	BV3	0.893			
	BV4	0.862			

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Ecological worldview	EW1	0.861	0.771	0.868	0.688
	EW2	0.858			
	EW3	0.766			
Adverse consequences for valued objects	AC1	0.880	0.831	0.899	0.748
	AC2	0.890			
	AC3	0.822			
Ascription of responsibility	AOR1	0.896	0.877	0.924	0.802
	AOR2	0.902			
	AOR3	0.890			
Pro-environmental personal norms	PPN1	0.864	0.892	0.925	0.756
	PPN2	0.882			
	PPN3	0.845			
	PPN4	0.886			
Attitude toward the behavior	ATB1	0.868	0.877	0.915	0.730
	ATB2	0.849			
	ATB3	0.856			
	ATB4	0.845			
Subjective norms	SN1	0.877	0.886	0.929	0.814
	SN2	0.914			
	SN3	0.915			
Perceived behavioral control	PBC1	0.833	0.843	0.906	0.762
	PBC2	0.901			
	PBC3	0.883			
Behavioral intention	BI1	0.850	0.845	0.907	0.764
	BI2	0.883			
	BI3	0.889			

Discriminant validity has been evaluated using the heterotrait-monotrait correlation ratio. The testing results in Table 3 demonstrate that none of these values exceeded the conservative threshold of 0.85, indicating discriminant validity. Therefore, the discriminant validity of the measurement model is appropriate.

Table 3 Heterotrait-Monotrait Ratio index of the research model

Items	AC	AOR	ATB	AV	BI	BV	EV	EW	PBC	PPN	SN
AC	-										
AOR	0.847										
ATB	0.638	0.679									
AV	0.444	0.428	0.535								
BI	0.628	0.704	0.780	0.459							
BV	0.511	0.443	0.562	0.697	0.548						
EV	0.419	0.448	0.400	0.697	0.383	0.482					
EW	0.842	0.678	0.606	0.515	0.550	0.596	0.359				
PBC	0.557	0.595	0.773	0.469	0.696	0.437	0.383	0.531			
PPN	0.738	0.813	0.808	0.479	0.781	0.505	0.461	0.637	0.600		
SN	0.521	0.534	0.728	0.384	0.719	0.393	0.417	0.432	0.481	0.749	-

Note: Egoistic values - EV; Altruistic values - AV; Biospheric values - BV; Ecological worldview - EW; Adverse consequences for valued objects - AC; Ascription of responsibility - AOR; Pro-environmental personal norms - PPN; Attitude toward the behavior - ATB; Subjective norms - SN; Perceived behavioral control - PBC; Behavioral intention - BI.

4.3 Structural model

Multicollinearity, R-squared value, and the statistical significance known as the P-value of structural connections are used to examine the structural model. In this research, the VIF (variance inflation factor) values are below five, indicating that multicollinearity is not a significant problem. Adjusted R-squared values have been calculated for four dependent variables: "ecological wordview" (0.271), "adverse consequences for valued objects" (0.453), "ascription of responsibility" (0.523), "pro-environmental personal norms" (0.518), "attitude toward the behavior" (0.513), "subjective norms" (0.443), "perceived behavioral control" (0.275) and "behavioral intention" (0.553). Table 4 shows the path coefficients of major effects.

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Table 4 PLS-SEM results

|	Path	VIF	Path coefficient (β)	P-value	Result
H1	Egoistic values → Ecological worldview	1.616	0.028	0.669	Not supported
H2	Altruistic values → Ecological worldview	2.111	0.173	0.020	Supported
H3	Biospheric values → Ecological worldview	1.620	0.386	0.000	Supported
H4	Ecological worldview → Adverse consequences for valued objects	1.000	0.673	0.000	Supported
H5	Adverse consequences for valued objects → Ascription of responsibility	1.000	0.723	0.000	Supported
H6	Ascription of responsibility → Pro-environmental personal norms	1.000	0.720	0.000	Supported
H7	Pro-environmental personal norms → Attitude toward the behavior	1.000	0.716	0.000	Supported
H8	Pro-environmental personal norms → Subjective norms	1.000	0.666	0.000	Supported
H9	Pro-environmental personal norms → Perceived behavioral control	1.000	0.524	0.000	Supported
H10	Attitude toward the behavior → Behavioral intentions	2.521	0.296	0.000	Supported
H11	Subjective norms → Behavioral intentions	1.702	0.325	0.000	Supported
H12	Perceived behavioral control → Behavioral intentions	1.794	0.256	0.000	Supported
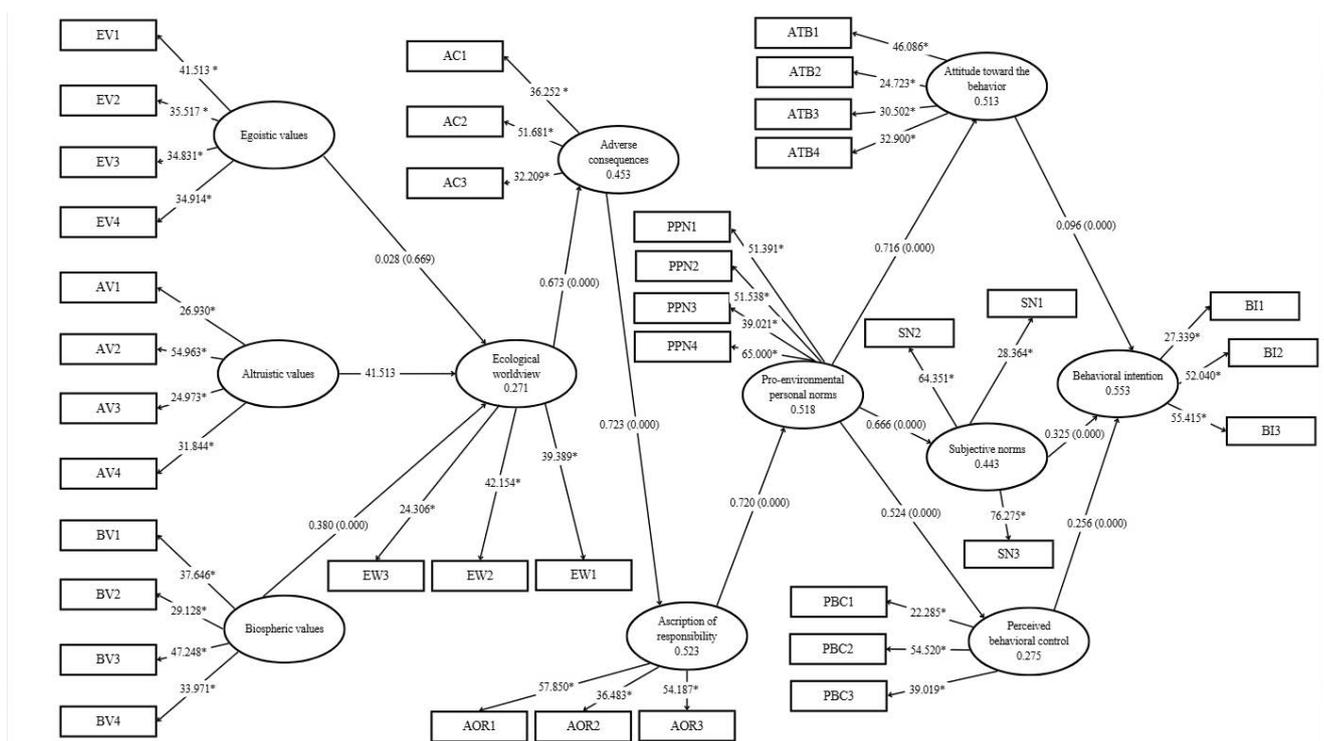
Figure 2 PLS-SEM results

*Note, *: T-statistic*

Table 4 shows that all main effects are statistically significant at the 5% level or lower. Furthermore, the directions of most path coefficients match our expectations, indicating that all hypotheses except H1 are supported. Regarding significant relationships, altruistic values (β = 0.173, p = 0.021) have a positive influence on ecological worldview, supporting H2. Likewise, biospheric values (β = 0.380; p = 0.000) demonstrate a substantial positive impact on ecological worldview, confirming H3. These results (Figure 2) emphasize that individuals with altruistic and biospheric orientations are more likely to adopt an ecological worldview, reflecting the essential role of these values in fostering environmentally conscious thinking. Moreover, ecological worldview has a significant impact on adverse consequences for valued objects (β = 0.673, p = 0.000), supporting H4. This relationship highlights the importance of ecological awareness in recognizing risks to valued objects. Following this, adverse consequences for valued objects has a strong influence on ascription of responsibility (β = 0.723, p = 0.000), supporting H5. This indicates that understanding negative environmental consequences motivates individuals to take responsibility for addressing these challenges. Next, ascription of responsibility has a significant effect on pro-environmental personal norms (β = 0.720; p = 0.000), supporting H6 and highlighting its role in shaping norms that encourage pro-environmental behaviors. A pro-environmental personal norm strongly impacts attitude toward the behavior (β = 0.716; p = 0.000), supporting H7. This suggests that individuals with strong personal norms regarding pro-environmental behavior are likely to develop favorable attitudes toward such actions. Similarly, pro-environmental personal norms also significantly influence subjective norms (β = 0.666; p = 0.000), supporting H8. This

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highlights the role of personal norms in shaping social perceptions and expectations regarding pro-environmental behavior. The relationship between pro-environmental personal norms and perceived behavioral control is also significant (β = 0.524, p = 0.000), confirming H9. This suggests that stronger personal norms positively enhance an individual's perception of their ability to perform pro-environmental behaviors. Furthermore, attitude toward the behavior has a significant effect on behavioral intention (β = 0.296, p = 0.000), supporting H10. This underscores the importance of positive attitudes in encouraging intentions to engage in pro-environmental actions. Subjective norms also exhibit a statistically significant positive impact on behavioral intention (β = 0.325; p = 0.000), validating H11 and emphasizing the role of social influences in shaping intentions. Lastly, perceived behavioral control has a significant influence on behavioral intention (β = 0.256; p = 0.000), supporting H12. This finding highlights the critical role of perceived ease or difficulty in performing a behavior in forming behavioral intention. Conversely, egoistic values do not exhibit a significant relationship with ecological worldview (β = 0.028; p = 0.652), rejecting H1. This finding suggests that self-centered motivations might not align with ecological thinking.

4.4 Discussion

The Vietnamese fuel-vehicle ban provides significant real-world validation for our study. This policy is projected to dramatically accelerate consumer adoption of electric vehicle-based delivery services, especially in urban last-mile logistics. While internal motivations such as biospheric values and moral norms remain key drivers, regulatory mandates and infrastructure availability will become equally influential on consumer choices after the ban. Our research highlights the possibility of applying electric vehicles instead of gasoline-powered vehicles in last-mile logistics services. Utilizing the Value-belief-norm framework [14], this research attempts to study how the framework's components affect consumers' behavioral intention in using electric vehicles for last-mile logistics services that carry parcels. According to the results, most hypotheses were accepted and showed a positive relationship. Two of the value orientations, altruistic and biospheric, positively affect ecological worldview, which means consumers who love nature have more green consumer behaviors [31].

On the other hand, there is no evidence to support the hypothesis that egoistic values are related to ecological worldview. Perhaps in this data sample, ecological worldview is not influenced by concerns about social dominance, wealth, and authoritative power affecting others. Another explanation is that people with a self-centered mindset are also less inclined to prioritize environmental-benefitting behaviors unless they directly impact their personal lives. For example, adopting electric delivery vehicles may not be regarded as an environmentally friendly practice but rather as a practical convenience. The following positive relation concerns the ecological worldview and adverse consequences for value objects, and adverse consequences for value objects and ascription of responsibility, and then ascription of responsibility and pro-environmental personal norms. This correlation suggests that a person must be aware of the potential consequences of their behavior before feeling responsible for engaging in that behavior and admitting their contribution is valuable. Moreover, consumers with a more urgent perception of environmental issues tend to have a more favorable perspective toward green consumption activities, including the use of electric vehicle services, which is a perfectly relevant statement.

This study also presented a positive relationship between pro-environmental personal norms and attitude toward behavior, subjective norms, and perceived behavioral control. For example, the higher a consumer's moral bond with pro-environmental norms, the higher the consumer's perceptions and expectations in using electric vehicles' last-mile logistics services for pro-environmental purposes [32]. The last correlation is the positive relation between attitude toward the behavior, subjective norms, perceived behavioral control, and behavioral intention. There might be a significant change in consumers' intentions to act accordingly if their family, friends, or coworkers expect them to make pro-environmental, responsible choices.

4.5 Implications
4.5.1 Theoretical implications

First, this study tests and extends the Value-belief-norm framework by examining how it explains consumer support for last-mile electric delivery. Evidence shows that linking values to norms shapes preferences for green logistics, underscoring the need to foster a sense of individual duty if intentions are to translate into action in environmentally sustainable transport.

Second, the authors re-evaluate the ecological impacts of electric vehicles while probing the interplay of altruistic and biospheric motives. Results reveal that both altruistic values and biospheric values play a strong role in shaping choices about commercial delivery. This pattern emerges in contrast to earlier observations reported by de Groot and Steg (2008) [9]. Egoistic concerns, by comparison, exert only a weak influence when viewed alongside the larger environmental worldview. Collectively, the shift points to a growing number of consumers who now place ecological welfare ahead of personal gains such as lower costs or greater convenience.

Third, the authors integrate findings from previous research using the Value-belief-norm model in diverse settings [30] and tackle the shortcomings that plagued earlier EV-adoption studies. Consistent with the methodology developed

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by Lee et al. (2023) [10]. In recruiting participants for the survey, we restricted the sample to individuals who are well acquainted with and regularly use electric delivery systems. By inviting only acknowledged experts with extensive experience in the area, we ensured that the insights obtained would be both trustworthy and relevant for real-world applications.

Additionally, our work addresses several notable gaps in the literature by providing a more detailed examination of how personal values, environmental beliefs, and intentions to act sustainably align. By linking these elements, we clarify how people's core convictions and their attitudes toward nature influence the choice to switch to electric vehicles. Moreover, we extend existing theory by demonstrating that emerging technologies can indeed reshape everyday behavior. Building on Hwang et al. (2020) 's findings, we demonstrate that pairing new gadgets with strong environmental messaging can significantly enhance consumers' green motives, particularly in densely urban markets [28].

Last but not least, this study offers theoretical insights that are useful for both policy making and business planning. It supports earlier research that suggests both normative and motivational factors influence consumer choices [33]. Our study helps build strong frameworks for promoting green last-mile logistics by mapping the connections between consumers' values, beliefs, norms, and their willingness to use new, eco-friendly delivery methods. It broadens the theoretical range of the Value-belief-norm model.

4.5.2   Practical implications

The research integrates the Value-belief-norm framework with conventional ethical practices to enhance awareness of sustainable green consumption while also underscoring the pivotal role of cognitive behavior in environmental preservation, a theme extensively explored in the literature.

First, by establishing the connection between values, beliefs, and pro-environmental intentions, earlier studies have shown that altruistic motives, ecological concerns, and environmental values collectively drive the shift toward cleaner delivery methods, reaffirming the influence of individual environmental norms and reinforcing a sense of moral duty and ecological consciousness.

Moreover, this transition may also present significant constraints. Key areas of concern include the availability of financial assistance, investment in charging infrastructure, and the development of communication strategies targeted at vulnerable groups such as freelance delivery drivers and motorbike taxi operators. Without such measures in place, the policy could unintentionally widen social inequalities and weaken its intended environmental and public health outcomes.

Furthermore, consumer engagement can be enhanced through marketing approaches that promote carbon footprint reduction, align with global sustainability targets, emphasize collective behavioral expectations, and facilitate informed decision-making. Logistics firms, in turn, can enhance consumer loyalty by embedding these insights into their corporate social responsibility initiatives. Companies actively incorporate sustainability into their business practices and marketing efforts, often receiving favorable responses from consumers.

Finally, by incorporating sustainability principles into incentive schemes, companies can motivate users to choose electric vehicle-based transportation, thereby reinforcing pro-environmental behavior and gaining a strategic advantage in the logistics sector. Both monetary and non-monetary rewards, such as discounts, loyalty points, or public acknowledgment for eco-friendly choices, can play a crucial role in fostering sustainable consumption habits.

4.6   *Limitations and future research*

Despite offering valuable insights into consumer behavior toward electric vehicle based last-mile logistics services, this study has certain limitations. First, the data were collected through a cross-sectional survey design, which restricts the ability to capture dynamic behavioral changes over time. Future studies could adopt longitudinal or experimental designs to understand better how consumer perceptions evolve as exposure to electric vehicle logistics services increases. Second, while this research focused on Xanh SM as a representative case of electric vehicle adoption in last-mile logistics, it did not compare multiple service providers or vehicle brands. Broader comparative studies encompassing diverse electric logistics providers would enhance the generalizability of findings. Third, although the model integrated well-established psychological constructs, it did not account for contextual or infrastructural variables such as delivery time reliability, electric vehicle charging infrastructure, or service availability across geographic regions. Future research could incorporate these operational and contextual factors to provide a more holistic understanding of the determinants influencing electric vehicle-based delivery adoption. Finally, expanding the sample to include respondents from different socioeconomic backgrounds and regions could further enrich the insights and support more robust policy and managerial recommendations.

Appendix A

All of the measurements of this study were adapted from previous validated studies and used a 7-point Likert scale, ranging from 1 "strongly disagree" to 7 "strongly agree". The measurement of three value orientations: egoistic, altruistic, and biospheric was derived from studies of Hwang et al (2020) with 4-items for each value [28]. Ecological worldview was assessed using 3 items adapted from Kiatkawsin and Han (2017) [29]. The constructs of adverse consequences for

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valued objects (3 items) and ascription of responsibility (4 items) were measured following the approach of Youn et al. (2020) [30]. The pro-environmental personal norm was also measured using 4 items adapted from Youn et al. (2020) meanwhile the constructs of attitude toward the behavior (4 items) were operationalized based on Lee et al. (2023) [10,30]. Subjective norms (3 items) was measured using items adopted from Youn et al. (2020) [30], while perceived behavioral control (3 items) and behavioral intention was based on the scale developed by Lee et al. (2023) [10].

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Electric vehicles for cleaner urban logistics: what motivates consumers to choose green delivery?
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Towards a sustainable automotive supply chain: a critical and systematic literature review of supplier selection criteria

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Keywords: automotive supply chain, supplier selection criteria, sustainability, resilience.
Abstract: The automotive supply chain faces increasing pressure to align supplier selection processes with sustainability and resilience goals while adhering to rigorous industry standards. However, many companies still rely on the traditional approach by considering mainly the piece price as criteria for supplier selection, and this approach can destroy the logistic flows and the supply chain performance. In this context, this paper aims to present a systematic literature review of over 100 peer-reviewed articles and studies that broaden current theoretical knowledge by identifying key Sustainable Supplier Selection Criteria. The methodology consists of three main steps. Firstly, the research was conducted using major academic databases between 2014 and 2024, such as Scopus, Web of Science, and Elsevier. Secondly, a database was developed to extract the most cited dimensions in the literature review. Finally, the criteria and sub-criteria identified from the reviewed literature were analyzed through a frequency analysis to determine the most frequently cited sub-criteria within each dimension. The findings show that six main dimensions are most cited in the literature: Economic, Social, Environmental, Green, Circular, and Resilience. Based on these results, we proposed the Sustainable Supplier Selection Concept (3SC Model), which integrates the six dimensions and will be further detailed through the criteria identified and presented in the results section. This model provides a comprehensive framework to guide both researchers and practitioners in developing more sustainable and resilient supplier selection systems.

1 Introduction

Global geopolitical processes, such as trade wars, climate change and pandemics, are radically restructuring the world economy. Global supply chains are undergoing significant changes due to geopolitical disruptions, economic instability, technological advances and cultural transformations [1]. Furthermore, the Automotive Supply Chain has faced significant transformations, impacted by electrification, digitalization and global challenges. These challenges include climate change, Industry 4.0 and various disruptions such as the COVID-19 pandemic and wars. Because of these changes, there is a high necessity for companies to focus on developing resilient and sustainable supply chains. Resilient supply chains are specified by their ability to support disruptions, recover efficiency and sustain continuous operations. However, this evolution has made supplier selection a crucial component in guaranteeing long-term sustainability and improving performance within supply chains.

The success of a supply chain and a robust logistic flow mainly depend on an effective supplier selection process (SSP), which is essential for maintaining sustainability and achieving the necessary standards. They underline three critical flows within the supply chain: materials, information, and money. These elements move from upstream suppliers, responsible for raw materials, to downstream producers, who handle final products [2].

Over the years, the aspect of green supplier selection has evolved as a crucial concern in the global green supply chain. Research by [3] explores integrating dynamic supplier risks and green market segmentation into SSP.

Sustainability in supply chain management (SCM) focuses on incorporating environmentally and socially responsible practices into business operations. It is based on the Triple Bottom Line framework, which emphasizes a balance between environmental care, economic success, and social fairness. Recent research highlights that sustainable SCM not only addresses environmental issues but also includes social and ethical aspects. Many businesses are now taking a more comprehensive approach to SCM, aiming to reduce their environmental impact while ensuring ethical sourcing and fair labor practices. This trend is particularly noticeable in industries like automotive, where selecting sustainable suppliers has become a top priority [4].

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The problematic that we are trying to resolve in this paper is that several automotive companies are still using the old supplier selection approach based on one single criterion which is Piece Price, and it is not valid any more to consider only the piece price, since there are other qualitative and quantitative criteria to be considered and that's precisely where this article aims to contribute by listing the mains criteria that should be used by leaders to nominate the sustainable supplier. To achieve this goal, the study addresses the following research questions:

- **RQ1:** What are the main sustainability dimensions considered in supplier selection within the automotive industry?
- **RQ2:** What are the key criteria associated with each sustainability dimension as identified in the existing literature?
- **RQ3:** How can these dimensions and criteria be integrated to enhance sustainability and resilience in the automotive supply chain?

The structure of this paper consists of 6 sections: after the introduction, section 2 provides a Critical and Systematic literature review of supplier selection criteria for automotive industry. In section 3 we present the methodology used to extract data and to list the significant criteria. Section 4 aims to present the result obtained from the systematic literature review. In Section 5 we discuss the results, and we clarify the linkage between the 7 terms constituting the long-term sustainability concept for supplier selection. Section 6 concludes our work's result and highlights some perspectives for future research.

2 Literature review

The supplier selection topic has been a key area of interest for researchers since the 1960s, with several articles and papers addressing the importance of evaluating suppliers' performance based on multiple criteria. Given the complex nature of these decisions, which require input from various departments and stakeholders, the supplier selection is considered as a multi-criteria decision-making (MCDM) task. Through the years, the process has evolved to incorporate sustainability factors, considering the economic, social, and environmental impacts of suppliers. Moreover, it is important to differentiate between 3 types of suppliers. The traditional one focuses on maximizing economic benefits, while the green supplier strives to balance both economic and environmental goals. Lastly, the sustainable supplier aims to optimize the benefits across the economy, society, and environment [5].

2.1 The automotive supply chain

The automotive supply chain is a very challenging area, facing several issues. To better understand its complexity, it is important to recognize that the automotive supply chain is divided into four fundamental steps (as mentioned in Figure 1): Raw Materials (RM) from suppliers, manufacturing sites for the Original Equipment Manufacturer (OEM), dealerships, and the final customer.
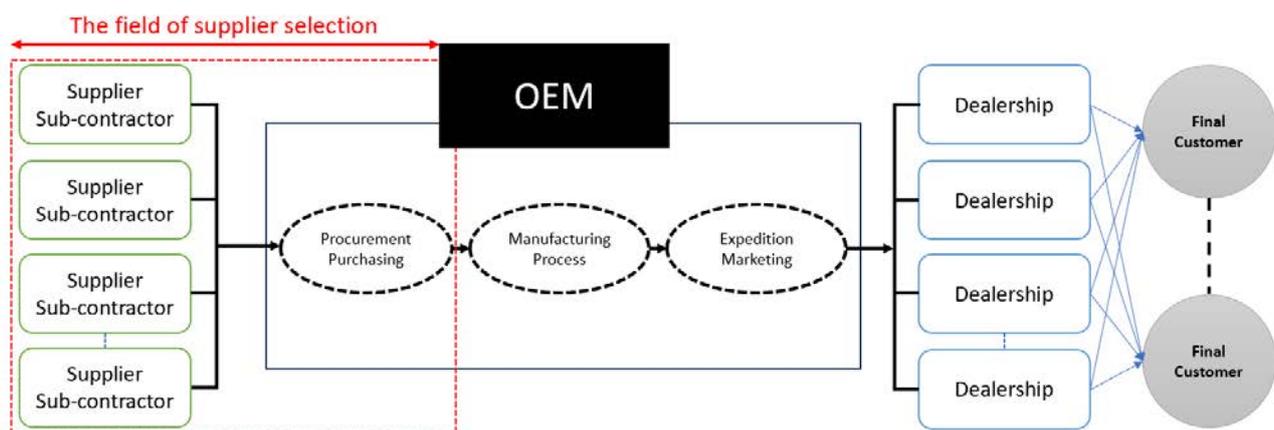
Figure 1 The process flow of automotive supply chain

Within each step, there are several risk factors and complexities who can impact the fluidity of the supply chain and logistic flows, especially the ones related to the RM from supplier as this is the first step in the supply chain flow and for sure, any risk at this step can destroy the whole chain value and logistic flows.

2.2 Supplier selection criteria (SSC)

Vendor or supplier selection problem is not a recent topic where industries and researchers are working on to find and develop new solutions to help the purchasing department choose a sustainable collaborator in supply chain value.

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Obviously, the ability to define and choose suitable criteria are the key elements for companies to make the right decision about the supplier who will be identified to develop the project in the correct way.

In this paper, we aim to study more than 100 articles and extract all criteria and sub-criteria from those studies and summarize them in one database to have at the end the top cited criteria per dimension, and here in this section we cited only the most important ones (around 27 articles from Web of Science and SCOPUS).

There are several literature reviews done previously since 1966 when Dickson did a very interesting study about SSC. Weber gives us a clear idea about the interest that was given in the past to vendor selection field, and we understood why the SSP was, and still a strategic element for companies and specifically for purchasing team to make the right decision. A classification and review of 74 articles since 1966 was done to conclude that 23 criteria are classified by importance (based on Dickson study): 4 criteria extreme importance, 9 criteria considerable importance, 9 criteria average importance and 1 criterion slight importance.

According to [6], a literature review has been performed based on 82 reviewed papers to list the different supplier selection approaches that have been used between 1990 and 2019 and consider environmental, economic, and social aspects, simultaneously. Coupled with, [7] presents a literature review for SSC from 1995 till 2007 where the articles and studies published from 1995 to 2005 focus on Quality, Capabilities, Delivery, Services, Technology, Finance, Relationships, and management. Environmental risks highlighted in 2007, becoming one of the crucial SSC. By the same token, [8] presents a literature review which includes the list of Sustainable Supplier Selection Criteria (SSSC). This list includes 15 criteria shared between the main 3 sustainable aspects (economic, social, environmental).

In [9], a literature review was done on sustainable supplier topic with a special interest on approaches treating monitoring and development of decision-making in sustainable supplier selection, and as respond to the question number 3 in the paper, 143 peer-reviewed studies between 1997 and 2014 have been verified to list 34 criteria divided on the 3 dimensions of sustainable supplier management (economic, social, environmental).

Additionally, [10] presents a rich literature review about the main field related to supplier selection topic as strategies and approaches used including selection criteria. 326 papers published between 2000 and 2021 were reviewed and as we are focusing on SSC, we can list the criteria below presented in Figure 2.
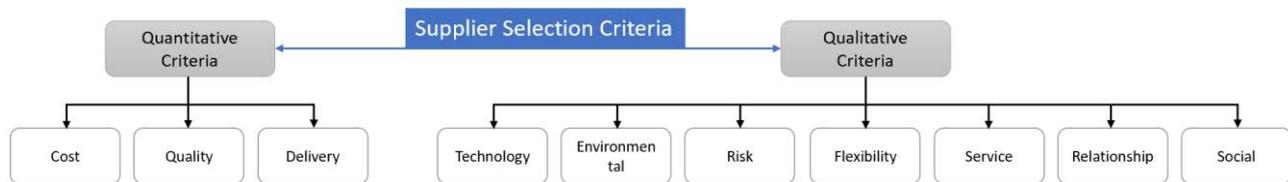

Figure 2 SSC from [10]

Furthermore, [5] presents a sustainable performance measure based on a systematic literature review and return of experience from experts in industry. In the paper we can find more than 30 criteria as a mix of traditional criteria (Quality, Delivery, Cost) and new criteria such as the alliance, training and education, governmental relations impact, and contracts. The study also follows the logic of the stakeholder theory to measure the social responsibility aspect. And in [11], the study identifies more than 14 criteria mixed between economic, social, environmental, green aspect, and the main criteria are green level of product and design, recycling, quality, service level and price.

Moreover, several studies and research have considered supplier selection problem as an extremely complex MCDM topic where the decision makers must evaluate both qualitative criteria (service, reputation, flexibility, etc.) and quantitative criteria (price and cost, delivery, etc.) to select a proper supplier [12]. Hence, [13] presents an integrated support system for supplier selection topic using a case of automotive industry, and the model identified 4 main criteria which are: price, quality, delivery, and service. Using the AHP and based on the expert's feedback, those criteria are classified as below: price, quality, delivery, and service. In addition, [14] discuss the sustainability concept as it becomes a philosophy of several industries, and the first step in this approach is to select a sustainable supplier. To do so, [14] presents an interesting fuzzy TOPSIS method to make the right decision and to select a sustainable supplier based on more than 30 SSC for an automotive manufacturer.

To be able to select a sustainable supplier who can maintain a good performance for a long period, [15] presented an integrated fuzzy logic and systems dynamics modeling approach where they considered 6 sustainable factors: Quality, Environmental Competencies, Safety Work, Information Disclosure, Green Design, and Policy Respect.

Likewise, [16] presents a new MCDM method that helps to choose and weigh the criteria used for SSP. As result of this proposed method, we can find more than 80 criteria which were classified into four groups: costly, complementary, critical, and priority. And according to [17], the authors contribute on a tedious task which is the selection of green supplier by using an MCDM framework, and a case study was applied in the Indian automotive industry based on 9 combined environmental and conventional criteria.

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There is another good study which uses machine learning and Random Forest approach to contribute on classification of relevant criteria for supplier selection problem [18], and the outcome of the study concludes with the classification of 30 potential criteria where nine of them were identified as critical in Table 1.

Table 1 SSC ranking according to [18]

Critical Criteria	Priority
Quality	1
Delivery On Time	2
Material Price	3
Information sharing	4
After sales services	5
Lead time	6
Quantity discount	7
Occupational health and safety system	8
Transportation cost	9

The automotive industry is increasingly prioritizing sustainability across its entire value chain, driven by regulatory pressures, consumer demand, and corporate responsibility goals. Therefore, [19] is one of the articles who give a significant interest to the sustainable supplier selection topic from the 3 aspects (environmental, economic, and social). Furthermore, the study aims to add the aspect of COVID-19 as the 4th aspect because it is affecting significantly the SSP, and the emergence of COVID-19 pandemic becomes a crucial criterion that companies must take into consideration to ensure a sustainable supply chain. An MCDM approach was presented in the paper and, to demonstrate the effectiveness, a case study is illustrated in automotive industry in Vietnam. 5 criteria have been considered as the most important: Price and Cost, Wellbeing of suppliers, Safety and health practices, Economic recovery programs and the use of personal protective equipment.

Based on [20], In general, most supplier selection studies evaluate sustainability based on three axes (Social, environment, and economy) and consider 5 majors to evaluate and ensure sustainability during SSP by adding Quality of relationship and Global risk dimensions. Similarly, [21] considered sustainability as a key element for supplier selection and evaluations problem and based on the literature (26 articles from 2008 till 2015) and feedback from experts, the author identified 3 major dimensions of criteria and 22 SSSC.

Social issues have become one of the major risk managements which is impacting the global supply chain. According to [22], a quantitative analytical approach was presented to discuss social risks of global supply chains, and as case study, the author chooses the application of the approach to supplier selection problem in the automotive industry. In the same line, [23] considers the sustainability aspect in the proposed study and performed a literature review to list the sustainable criteria, besides on that several meetings were performed with decision makers in the iron and steel industry to classify 66 SSSC on 3 dimensions (economic, environment, social).

According to [24], an empirical study was done to confirm that the influence of reputation factors on supplier selection is more important than other classical criteria, at least in the European Automotive Industry.

Recently, Several OEMs aimed to assess the supplier sustainability performance based on the self-assessment questionnaire (SAQ), this article uses the SAQ which is becoming a crucial tool in the automotive industry to evaluate the sustainability performance for suppliers [25].

As the green aspect become a crucial aspect for companies to be highlighted, [26] took into consideration both aspects (Green and sustainability) for SCM. Green SSP is a very challenging topic who can significantly conclude the success or failure of a business. The study proposed an MCDM method to select a suitable green supplier for a green and sustainable supply chain in the automotive industry.14 green criteria were identified in this paper.

On the other hand, [27] contributes to resolving the supplier selection problem and order allocation in the automotive industry, and the environment, social and economic factors are selected based on experts' opinions. Because supplier selection is the key for a successful supply chain, [28] presents an integrated approach for sustainable supplier selection problems. 13 criteria are considered in this work and customer satisfaction was the criterion of highest priority, followed by long-term relationships, and then pollution control.

According to [29], we find a very interesting SSP that can be used by automotive companies to select a suitable supplier. This process is divided into 3 phases and for each phase there are specific criteria to be considered for final supplier ranking. Those criteria are Quality performance, Delivery performance, financial performance, Launch performance and some key Indicators such as Overall Equipment Effectiveness OEE, Certification (International Automotive Task Force IATF, ISO 14001), Capacity, Political Stability and Price.

Recent years have underscored the paramount importance of resilience within the supply chain. Resilience refers to an organization's capacity to prepare for, adapt to, respond to, and swiftly recover from unexpected disruptions. The automotive sector has faced significant challenges, including semiconductor shortages, geopolitical tensions, natural disasters, pandemics like COVID-19, and economic fluctuations such as inflation. Consequently, effective supplier

selection in the automotive industry now critically integrates resilience, moving beyond mere cost considerations to encompass a deeper evaluation of a supplier's financial health, adaptability, and ability to ensure continuity amidst unforeseen global complexities. According to [30], the resilience aspect of supplier selection is considered by identifying 12 criteria that can be used: Management and organization support, strategy vision and corporate commitment, community influence, position in the market and reputation, financial stability, logistics capabilities, environmental respect, vulnerability and risk management, sustainability level of suppliers, supplier responsiveness, velocity of supply chain, and training.

Supplier selection, a crucial process for automotive manufacturers, is now being influenced by the circular economic principles. According to [31], the relationship between circular economic and SCM became more and more significant, especially in the automotive industry because of critical materials used for Electrical Vehicles (EV) cars manufacturing. As the SSP is a crucial field in supply chain, this study aims to apply a MCDM approach for supplier selection in a circular supply chain. Electrical vehicles were chosen to be a case study for this paper. The result of the study contributes to identifying the main criteria for circular supplier selection problem based on 3 steps:

- literature review,
- assessment of criteria by experts from the procurement department in the automotive industry,
- determination of the mutual influence of the criteria.

Environmental certifications, environmental standards, resource consumption, and waste generation are the significant criteria which were identified for circular supplier selection in Electrical Vehicles (EV) supply chains.

Additionally, [32] highlighted how the life cycle of product can be extended by presenting a circular economic model which involves reusing, recycling, sharing, refurbishing, and repairing existing materials and products if possible, and the authors analyze the relevant SSC from different aspects: Environment, Economic, Social, resilience and circular.

To close this section, we can say that this paper addresses gaps in current research by conducting a systematic literature review of more than 100 studies published between 1960 and 2024. The study identifies key trends, research gaps, and opportunities in supplier selection. It particularly focuses on sustainability and resilience, emphasizing their strategic importance in building effective supply chains.

3 Methodology

This study presents the structured methodology aimed to identify, classify, and analyze supplier selection dimensions and criteria within the automotive industry. The research approach consists of three steps, as presented in figure 3.
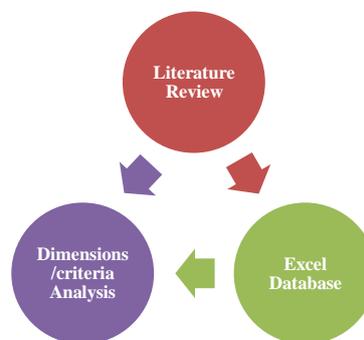
Figure 3 Summarized methodology

Our research starts with a literature review, which focuses on identifying and analyzing scientific publications related to supplier selection criteria, sustainability, and resilience, particularly in the automotive sector. The review was carried out using scientific databases such as Scopus, Web of Science, Elsevier, Emerald, Taylor & Francis, Springer, IEEE, and Google Scholar. Focused on titles, abstracts, and full-text articles published between 2014 and December 2024. The results indicate that Engineering dominates the field (23.5%), followed by Energy and Environmental Science (13.7%), and Computer Science and Business (13.6%). Other discipline such as Decision Sciences (8.1%), Social Sciences (7.3%), Mathematics (2%), Economics and Finance (2%), and Materials Science (2%) also participate to this multidisciplinary domain. This disciplinary diversity suggests that responding to the supplier selection and sustainability challenges requires a strong interdisciplinary approach. Moreover, the number of publications increased between 2014 and 2024, especially after 2020, indicating the rising awareness in sustainability, transparency, and corporate responsibility in supply chains (Figure 4).

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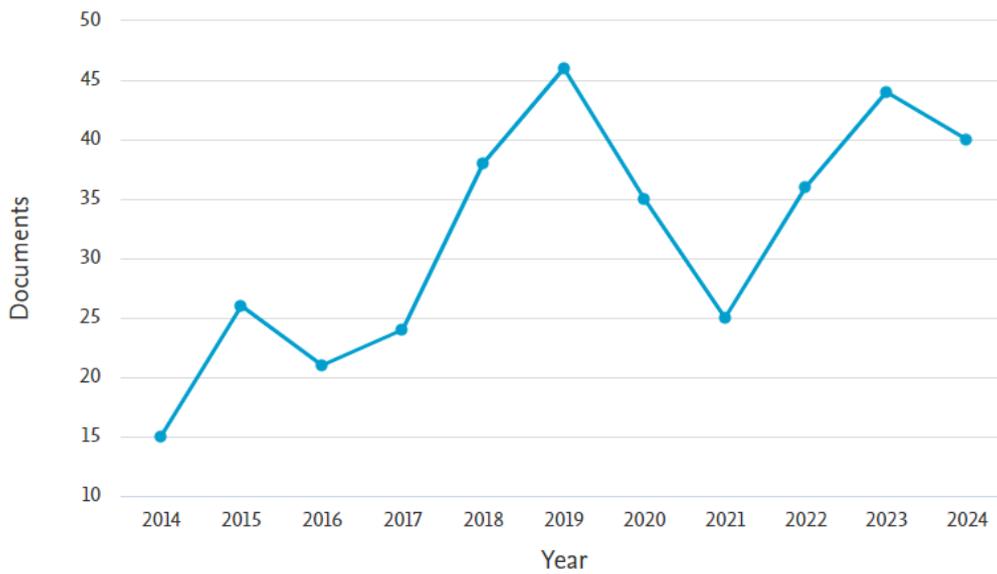
Figure 4 Evolution of publications on supplier selection

The papers and studies collected among the literature review were organized into an Excel database to ensure a consistent and systematic analysis of data. Each reviewed article was coded according to publication year, authors, journal, research methodology, and the supplier selection dimensions and criteria identified. Through this database we can identify six main dimensions more cited in literature review such as Circular, Green, Environmental, Social, Economic, and Resilience and more than 800 supplier selection criteria that will be classified and disused in the next section.

4   Results

From this literature review, only 10% of articles are before 2015 and 90% are later than 2015 which means the researchers are given more interest to supplier selection problem in the last decencies. Following the identification of over 800 supplier selection criteria (SSC) and sub-criteria, classified into six key dimensions (Circular, Green, Environmental, Social, Economic, and Resilience), this section highlights the most frequently cited criteria within each dimension.

4.1   Economic dimension

As illustrated in the figure 5, the quality management (e.g. Quality of product, certification, Quality rejects, Quality management system etc), Material Planning and Logistics MP&L management (Delivery, Leadtime, Logistics infrastructure, Inventory, etc) and Capabilities of company (Technology, production infrastructure, process capability, maintenance etc) are in the top of SSC list for economic dimension.
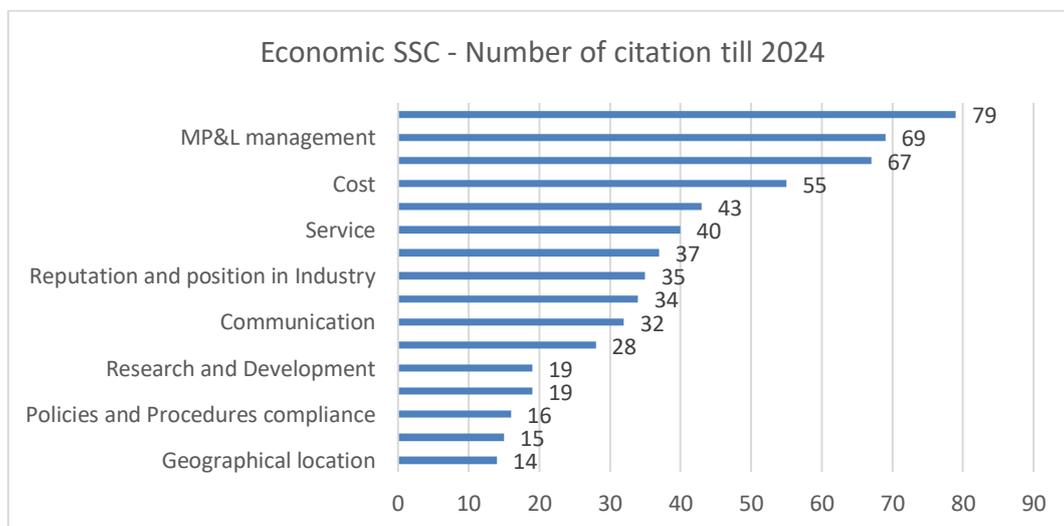
Figure 5 Top cited criteria for economic dimension

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4.2 Social dimension

According to the figure 6 , we can see clearly that the term of "**safety first**" is the objective of all companies and individuals, sfatey and health (Work safety, health insurance and programs, disiplinary and security practices etc), forced labor and human rights (Child labor, child abuse, The rights of employees, the rights of stakeholders, etc) and Human resources management (employee practices, Ethics, Job creation, career development, etc) are in the top of SSC list for social dimension.
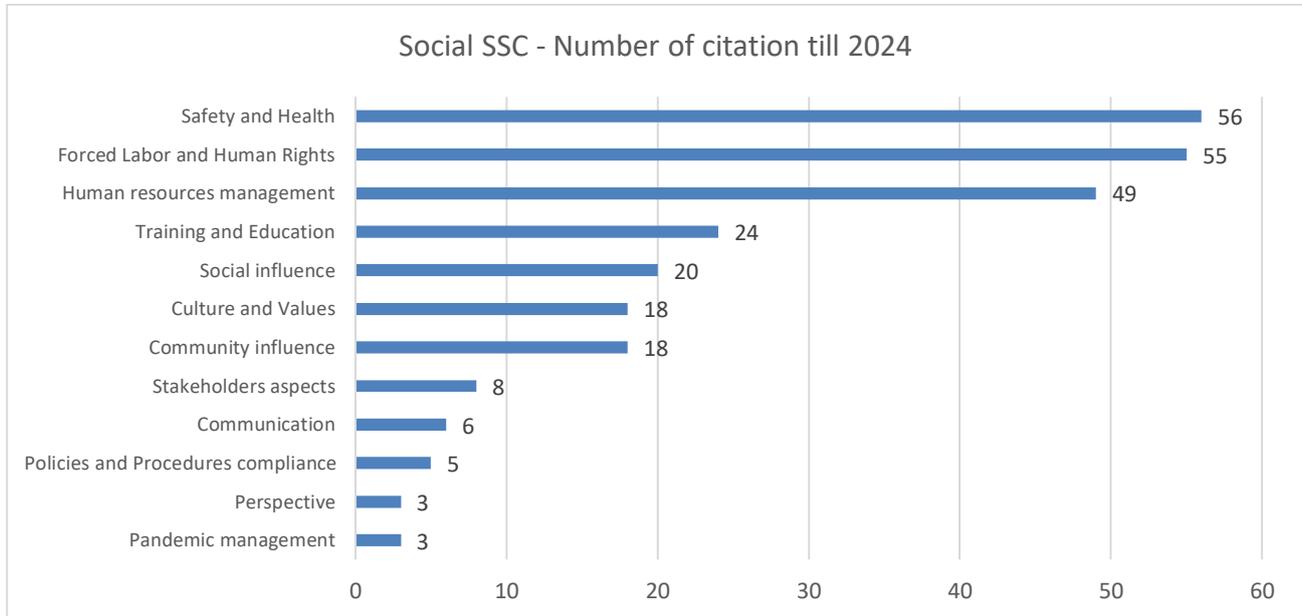
Figure 6 Top cited criteria for social dimension

4.3 Resilience dimension

The figure 7 illustrate the main Resilience SSC cited in literature. Resilience aspects (Agility, Attitude, Capacity, Closeness Relationship, Collaborative Plan, Communication Openness, Competency, Complexity, Cooperation, Critical Nodes, Density, etc) Flexibility and risk management are the top priority criteria for a resilient company.
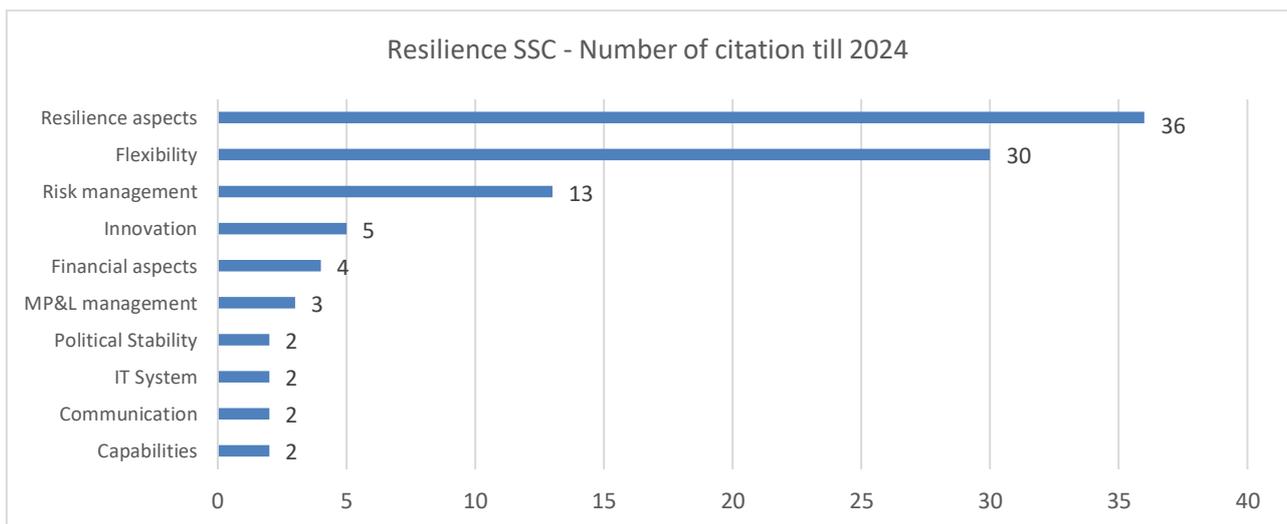
Figure 7 Top cited criteria for resilience dimension

4.4 Environmental dimension

The environmental dimension have a strong relationship with the green aspect and it is crucial for sustainability and competiviness. Environment Management System (eg ISO 14001), Pollution Control, Environment competencies, Eco-Design and Carbon emissions are in the top of Environmental SSC list (Figure 8).

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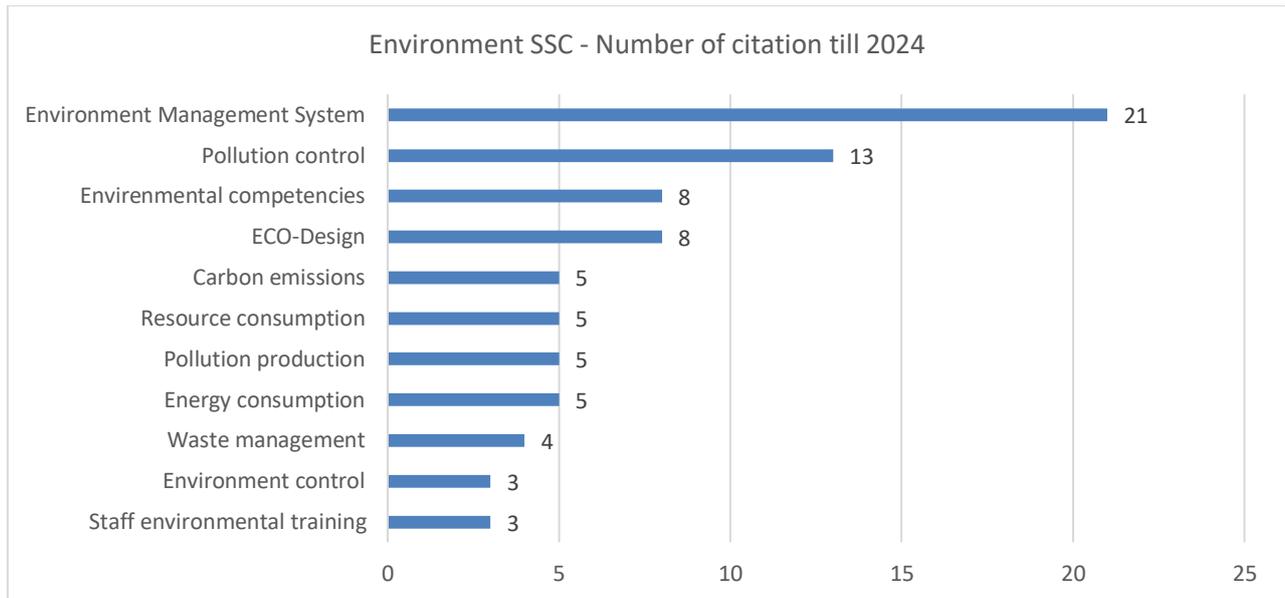
Figure 8 Top cited criteria for environmental dimension

4.5   Green dimension

The green dimension is the tendencee of reserchers and companies, due the climate change and the new international rules. To be competitor in the automotive market and to avoid penalities, the companies must take in consideration the green criteria listed in figure 9 for the supplier selection topic.
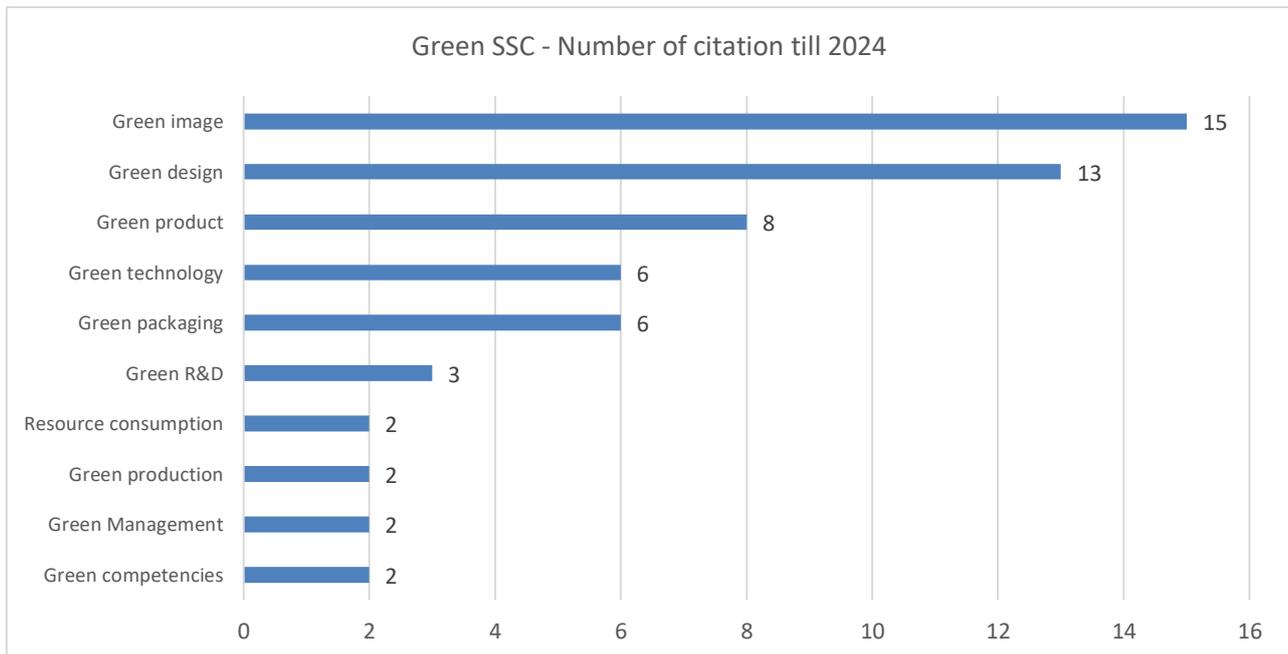
Figure 9 Top cited criteria for green dimension

4.6   Circular dimension

Circular Economic dimension is linked mainly to the green and enviromental dimension because the top criteria cited in literature are commun.Reuse and recycle are the core terms of circular economic, folowed by waste managemenet (waste water, waste energy, waste prevention, etc) as mentioned in figure 10.

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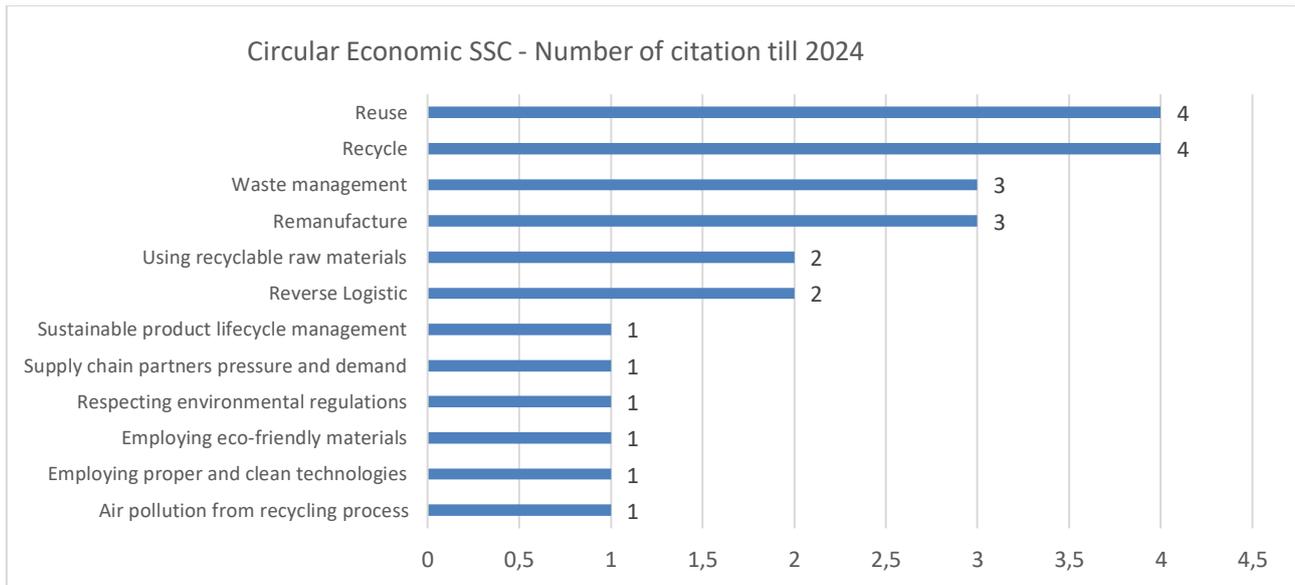
Figure 10 Top cited criteria for circular economic dimension

From these results, we can say clearly that the economic criteria: Quality management, MP&L management, capabilities and cost are the top cited ones, followed by social criteria: Safety and health, Forced Labor and human rights, and Human resources management, then we have resilience aspects such as Risk Management Capability, Flexibility and Adaptability, Financial Stability and Operational Health. And after that it comes environmental criteria like environment management system and pollution control. And at the end we find the green and circular economic impact as the recent dimensions in supplier selection field.

5   Discussion

The data from literature are very interesting and can be used by companies to establish a suitable system for supplier selection, and based on the literature review section, all selected articles were organized into Excel database to facilitate comparison and analysis. Each criterion from article was classified according to Circular, Green, Environmental, Social, Economic, and Resilience dimensions from which we derived the Sustainable Supplier Selection Concept (3SC model) for a long-term sustainability as mentioned in figure 11.
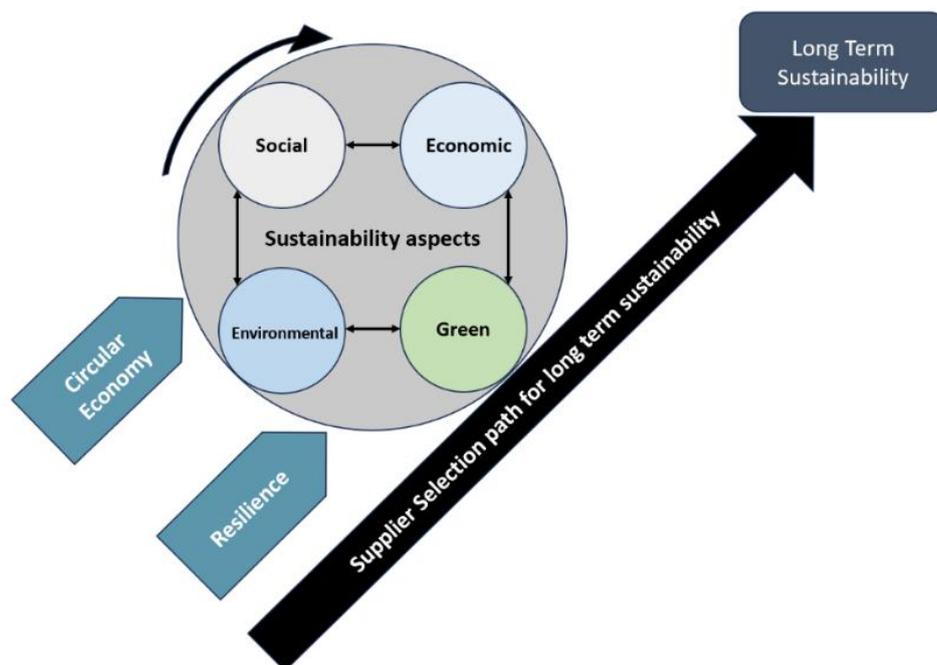
Figure 11 The sustainable supplier selection concept (3SC model)

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The seven terms (the six dimensions and sustainability) are deeply interconnected, forming a complex web of relationships crucial for sustainable supplier selection. Here is a breakdown of their links, explaining different facets of their connections:

- **Green Aspects → Environment Management**: Green aspects (e.g., reduced emissions, renewable energy, biodiversity) are the targets of effective environment management. Environment management strategies aim to protect and improve these green aspects.
- **Environment Management → Circular Economy**: A circular economy minimizes waste and pollution – key goals of environment management. By designing out waste and pollution, reusing materials, and regenerating natural systems, the circular economy directly supports good environment management.
- **Circular Economy → Economic Aspects:** The circular economy offers significant economic benefits. It creates new business models, reduces resource costs, and stimulates innovation, all contributing positively to economic aspects.
- **Economic Aspects → Social Aspects:** A strong economy generally leads to improved social well-being. Increased employment opportunities, better infrastructure, and higher standards of living are all positive social outcomes linked to a healthy economy.
- **Social Aspects → Resilience:** Socially cohesive and equitable communities are more resilient to shocks and stresses (economic downturns, environmental disasters, etc.). Strong social networks and support systems enhance the capacity to adapt and recover.
- **Resilience → Sustainability:** Resilience is crucial for achieving sustainability. A system's ability to withstand and adapt to change is essential for long-term viability – whether it's an ecosystem, a community, or a business model.
- **Sustainability:** This overarching concept integrates all the other elements. It requires a balance between green aspects, economic aspects, and social aspects, enhanced by effective environment management, a circular economy, and system resilience.

The links are not always linear. For instance, strong economic aspects (particularly those based on sustainable practices) can support better environment management and increased resilience. Similarly, improved social aspects (like community engagement in conservation efforts) can lead to better protection of green aspects. A circular economy directly contributes to both environmental protection (green aspects) and economic growth (economic aspects). And resilience is essential for maintaining all other aspects in the face of various challenges.

In essence, sustainability is the goal, achieved through careful management and integration of all these elements. They are interdependent; improvements in one area often positively impact others, while neglecting one can negatively affect the entire system. We can conclude that the 7 terms are interconnected, and they are constituting the concept of long-term sustainability.

6 Conclusion

From this systematic literature review, we can see clearly that the piece price is not the only criteria that leaders need to take into account for supplier selection as there are other more improtant criteria from the 6 different dimensions that we need to take in consideration before any nominations of suppliers.

This paper is a crucial source of data for researchers and academics who are working on supply chain improvement and mainly in supplier selection topics. It presents a clear concept (3SC model) to achieve the long-term sustainability by evaluating and selecting the most important criteria. The results show that sustainability aspects (economic, social, and environmental) and resilience are essential for the SSP, reflecting the growing need for sustainable and resilient supply chains. We also summarized the criteria and sub-criteria from the literature, focusing on areas like cost optimization, reducing environmental impact, and improving social relationships in the supply chain. This paper offers as well a valuable database from the literature that includes more than 800 criteria needed to choose sustainable suppliers in the automotive industry. We also found that circular economy and resilience are key to improving sustainability and achieving long-term goals.

From a discussion with experts in automotive, there are several criteria that can be add like flexibility of negotiation, payment flexibility, design change flexibility, value chain transparency, digital manufacturing data, emotional criteria, trust level between supplier and customer, penetration rate: number of projects developed between supplier and customer (to evaluate monopoly level).

However, there are still challenges. In the future, we plan to survey experts in the automotive industry to confirm the criteria found in the literature and discover new ones not yet mentioned. Additionally, we aim to analyze supplier selection methods and develop new artificial intelligence (AI) tools to improve process and select the suitable suppliers for a sustainable automotive supply chain.

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Balancing profits and planet: a game-theoretic particle swarm optimization for green inventory routing

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Abstract: In an era of heightened environmental awareness and increasing energy costs, sustainable logistics has become a critical focus in supply chain management. The Green Inventory Routing Problem (GIRP) extends the classic Inventory Routing Problem (IRP) by integrating environmental objectives—such as minimizing greenhouse gas (GHG) emissions—alongside traditional economic costs. This study proposes a novel Game-Theoretic Particle Swarm Optimization (GT-PSO) algorithm to address the GIRP, conceptualizing the discretization process as a strategic game to transform continuous swarm behavior into discrete logistics decisions. The objective minimizes a weighted cost function of transportation, inventory holding, and carbon emissions, supporting efficient management of material and transport flows. Thirteen benchmark instances representing different logistics network scales were used to evaluate performance against Genetic Algorithm (GA), Simulated Annealing (SA), and the commercial solver Gurobi. Results show that GT-PSO achieves the best-known solutions for medium- and large-sized problems with an average gap below 0.97%. ANOVA tests confirm statistically significant superiority, and coefficient of variation analysis highlights consistent performance. This research contributes an advanced optimization tool for sustainable logistics and distribution systems, helping managers balance economic efficiency with environmental responsibility.

1   Introduction

The confluence of globalized markets and mounting environmental pressures has compelled businesses to re-evaluate their supply chain strategies. Sustainable logistics management is no longer a niche concern but a central pillar of corporate responsibility and long-term viability [1]. Within this paradigm, Vendor-Managed Inventory (VMI) has emerged as a highly effective strategy for optimizing supply chain efficiency. In a VMI model, the supplier takes responsibility for managing the customer's inventory levels, leading to reduced overall costs through better coordination of production and transportation [2]. From a logistics perspective, optimizing the flow of materials, information, and transport resources across the supply chain has become essential to ensure both economic and environmental efficiency.

The operational challenge at the heart of VMI is the Inventory Routing Problem (IRP), first formally introduced by Bell et al. in 1983 [3]. The IRP integrates three critical decisions: 1) when to service a customer, 2) how much to deliver, and 3) how to combine deliveries into efficient vehicle routes [4]. By solving these decisions simultaneously, companies can achieve significant cost savings compared to managing inventory and routing separately [5].

However, traditional IRP models have predominantly focused on economic objectives, such as minimizing transportation and inventory holding costs [5]. The increasing urgency of climate change, driven by greenhouse gas (GHG) emissions from activities like transportation, necessitates an evolution of these models. This has given rise to the Green Inventory Routing Problem (GIRP), which extends the IRP by incorporating environmental impact factors, most notably CO_2 emissions from fuel consumption, directly into the optimization objective [6,7].

The GIRP, like its predecessor, is a combinatorial optimization problem classified as NP-hard [8]. This complexity means that finding a guaranteed optimal solution using exact methods is computationally intractable for real-world, large-scale instances. Consequently, the research community has largely turned to heuristic and metaheuristic algorithms to find high-quality, near-optimal solutions within a reasonable time frame. Methods such as Genetic Algorithms (GA) and Simulated Annealing (SA) are well-established; however, their performance often declines as problem scale increases. Existing PSO-based approaches also face a notable limitation—the discretization of continuous particle movements into routing decisions is usually handled by simple rounding or threshold rules, which can cause premature convergence and instability in complex GIRP settings. This limitation defines a clear research gap that motivates the development of a more adaptive, game-inspired discretization framework.

This paper makes a significant contribution to this field by proposing a novel Game-Theoretic Particle Swarm Optimization (GT-PSO). By framing the discretization process as a strategic decision-making game, our approach provides a new and robust mechanism for solving complex combinatorial optimization problems like the GIRP. Each step of the GT-PSO is designed to match the nature of GIRP: initialization creates diverse solutions for large search spaces; the game-based discretization allows probabilistic, adaptive routing choices; and iterative updates guide the swarm toward lower cost and emission objectives. This structure makes the proposed steps particularly suitable for addressing the combined economic-environmental trade-offs of GIRP. This study aims to:

1. Propose an improved metaheuristic algorithm, GT-PSO, for solving the green inventory routing problem with GHG emission costs.
2. Demonstrate the superior performance of the proposed method by rigorously comparing it against established metaheuristics (GA and SA) and a leading commercial solver (Gurobi) across a comprehensive set of benchmark problems.

The distinctive feature and contribution of this research lie in integrating game-theoretic reasoning into the PSO framework, enabling particles to make strategic, context-sensitive decisions rather than relying on purely stochastic updates. This mechanism improves convergence stability and scalability, distinguishing GT-PSO from conventional metaheuristics for green logistics.

The remainder of this paper is structured as follows: Section 2 provides a review of the relevant literature on IRP, GIRP, and the application of metaheuristics. Section 3 presents the formal mathematical model of the problem. Section 4 details the proposed PSO for GIRP methodology. Section 5 describes the computational experiments and presents a thorough analysis of the results. Finally, Section 6 offers conclusions, managerial implications, and directions for future research.

2 Literature review
2.1 The inventory routing problem
The Inventory Routing Problem (IRP) has been a subject of intensive research for over four decades since its inception by Bell et al. [3]. It addresses the integrated logistics planning of inventory management at customer locations and the routing of vehicles from a central depot to replenish them. A comprehensive review by Coelho et al. [5] highlights the evolution of IRP research, covering various problem characteristics such as single vs. multi-period horizons, deterministic vs. stochastic demand, and different inventory policies. The primary challenge of the IRP lies in its combinatorial complexity, which grows exponentially with the number of customers and the length of the planning horizon, making it a formidable computational task.

2.2 The green inventory routing problem
The transition from IRP to Green Inventory Routing Problem (GIRP) reflects a broader shift towards sustainability in operations research. The GIRP explicitly incorporates environmental objectives into its framework. Early works began to consider environmental aspects like fuel consumption as a proxy for both cost and emissions. More recent studies, as surveyed by Moghdani et al. [6] and Soysal et al. [10], formalize this by including emission costs, often derived from carbon taxes or emission trading schemes, directly in the objective function.

Key considerations in GIRP models often include the impact of vehicle load, speed, and type on fuel consumption and emissions [11,12]. For example, Cheng et al. modeled a GIRP with a heterogeneous fleet, allowing for the selection of more fuel-efficient vehicles [13], while Soysal investigated a closed-loop IRP for returnable items [14]. This study follows this trend by formulating an objective function that explicitly weights economic costs against GHG emission costs, providing a flexible framework for decision-makers.

2.3 Solution approaches for GIRP
Given the NP-hard nature of GIRP, research on solution methods is vast and varied.

2.3.1 Exact methods
For small-scale problems, exact methods based on Mixed-Integer Linear Programming (MILP) can find optimal solutions. Solvers like Gurobi and CPLEX employ sophisticated branch-and-cut or branch-and-price algorithms [15]. However, their computational time becomes prohibitive as problem size increases, limiting their practical application.

2.3.2 Metaheuristics
For medium- to large-scale instances, metaheuristics are the dominant approach. These high-level strategies guide the search for near-optimal solutions without guaranteeing optimality.

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- Genetic Algorithms (GA): GAs mimic natural evolution and have been applied to various IRPs [16]. They are effective at exploring the solution space but can sometimes suffer from premature convergence to local optima.
- Simulated Annealing (SA): SA is a probabilistic method inspired by the annealing process in metallurgy, which allows it to escape local optima [17].
- Particle Swarm Optimization (PSO): Introduced by Kennedy and Eberhart [18], PSO is a population-based algorithm inspired by the social behavior of bird flocks or fish schools. It is known for its conceptual simplicity and rapid convergence. While originally designed for continuous optimization problems, its application to discrete problems like routing requires a mechanism to map continuous particle positions and velocities to a discrete solution space. Various discretization techniques have been proposed, but finding an effective mapping remains a key challenge and an active area of research [19]. This research gap motivates our use of a novel game-theoretic discretization approach.

Despite extensive studies on metaheuristic approaches such as GA, SA, and PSO for GIRP, several research gaps remain. First, most PSO adaptations for GIRP rely on simplistic or ad hoc discretization methods that inadequately represent the combinatorial decision space, leading to premature convergence. Second, few studies integrate strategic decision frameworks, such as game theory, to enhance the decision-making behaviour of particles. Third, there is a lack of systematic benchmarking that evaluates algorithm robustness, scalability, and statistical significance across small to large problem sizes. To bridge these gaps, this study introduces a Game-Theoretic Particle Swarm Optimization (GT-PSO) that employs a structured, probabilistic game-based discretization mechanism, aiming to enhance both the accuracy and stability of GIRP solutions.

3   Problem formulation

This study addresses a multi-period, single-depot, multi-customer GIRP with a homogeneous fleet of capacitated vehicles. The objective is to determine the optimal delivery quantities, schedule, and vehicle routes over a finite planning horizon to minimize the total integrated cost of transportation, inventory, and GHG emissions.

Set and indices:
$N = \{1,2,\ldots,n\}$: Set of customers.
$N_0 = N \cup \{0\}$: Set of all nodes, where 0 is the central depot.
$V = \{1,2,\ldots,m\}$: Set of available vehicles.
$T = \{1,2,\ldots,H\}$: Set of time periods in the planning horizon.
$A = \{(i,j) \mid i,j \in N_0, i \neq j\}$: Set of arcs connecting the nodes.

Parameters:
d_{ij} = Distance from node i to node j.
c_{ij} = Transportation cost per trip from node i to j.
e_{ij} = GHG emission (e.g., in kg of CO_2) per kilometer between i and j.
q_{it} = Demand of customer i in period t.
Q = Capacity of each vehicle.
I_i^{max} = Maximum inventory capacity at customer i.
I_i^{min} = Minimum inventory level (safety stock) at customer i.
h_i = Inventory holding cost per unit per period at customer i.
α = Cost per unit of GHG emission (e.g., carbon tax).
β = A weighting factor ($0 \le \beta \le 1$) to balance economic and environment costs.

Decision variables:
$x_{ij}^{kt} \in \{0,1\}$: 1 if vehicle k travels from node i to node j in period t; 0 otherwise.
$y_{it} \ge 0$: Amount of product delivered to customer i in period t.
$I_{it} \ge 0$: Inventory level at customer i at the end of period t.

Mathematical model:
The objective function is to minimize the total cost, z:

$$\min \sum_{t \in T} \left[\sum_{k \in V} \sum_{(i,j) \in A} \left((1-\beta)c_{ij} + \beta\alpha e_{ij}d_{ij} \right) x_{ij}^{kt} + \sum_{i \in N} h_i I_{it} \right] \qquad (1)$$

Subject to:

$$I_{it} = I_{i,t-1} + y_{it} - q_{it}, \qquad \forall i \in N, t \in T \qquad (2)$$
$$I_i^{min} \le I_{it} \le I_i^{max}, \qquad \forall i \in N, t \in T \qquad (3)$$

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$$\sum_{i \in N} y_{ij} \leq Q \cdot \sum_{j \in N_0, j \neq i} \sum_{k \in V} x_{ij}^{kt}, \quad \forall t \in T \tag{4}$$

$$y_{it} \leq Q \cdot \sum_{j \in N_0, j \neq i} \sum_{k \in V} x_{ji}^{kt}, \quad \forall i \in N, \forall t \in T \tag{5}$$

$$\sum_{j \in N_0, j \neq i} x_{ij}^{kt} = \sum_{j \in N_0, j \neq i} x_{ji}^{kt}, \quad \forall i \in N_0, k \in V, t \in T \tag{6}$$

$$\sum_{j \in N} x_{0j}^{kt} \leq 1, \quad \forall k \in V, t \in T \tag{7}$$

The objective function (1) minimizes the weighted sum of transportation costs, emission costs, and inventory holding costs. Constraint (2) is the inventory balance equation. Constraint (3) ensures inventory levels remain within their allowed minimum and maximum bounds. Constraint (4) enforces vehicle capacity limits. Constraint (5) is a logical constraint ensuring that a delivery is made to a customer only if they are visited. Constraint (6) ensures route flow conservation. Finally, constraint (7) ensures each vehicle route starts and ends at the depot.

4   The Proposed Game-Theoretic PSO (GT-PSO) algorithm

To tackle the complexity of the formulated GIRP, we propose a Particle Swarm Optimization algorithm grounded in a game-theoretic framework. The primary challenge in applying PSO to routing problems is the translation of a continuous velocity vector into a discrete set of actions (i.e., whether to include an arc in a route or not). We conceptualize this challenge as a simple, repeated game played by each particle for each dimension of the solution space. In this game:

- The Player: The particle itself.
- The Actions: The particle has a discrete set of choices for each arc—'include' (1), 'exclude' (0), or 'maintain status quo'.
- The Strategy: The particle's strategy is a decision rule that maps the combined influences (cognitive, social, and inertial, represented by the continuous velocity value) to one of the discrete actions.

The Sig-bo game discretization, presented next, serves as the explicit implementation of this strategy, providing a probabilistic rule-set for this decision-making process.

4.1   *Fundamentals of particle swarm optimization*

Particle Swarm Optimization (PSO) is a population-based stochastic optimization technique where a population of candidate solutions, called a swarm of particles, moves through the D-dimensional problem search space. Each particle's movement is influenced by its own best-known position ($pbest$) and the entire swarm's best-known position ($gbest$). The velocity and position of each particle are updated iteratively. The modified velocity update equation, which includes an inertia weight (ω) to balance global and local exploration [20], is (8), (9):

$$v_{ij}^{t+1} = \omega v_{ij}^t + \phi_1 \beta_1 \left(pbest_{ij}^t - x_{ij}^t \right) + \phi_2 \beta_2 (gbest_j^t - x_{ij}^t) \tag{8}$$

$$x_{ij}^{t+1} = x_{ij}^t + v_{ij}^{t+1} \tag{9}$$

where ϕ_1 and ϕ_2 are cognitive and social acceleration constants, and β_1 and β_2 are random variables in [0,1].

4.2   *Sic-bo game discretization technique*

The primary challenge in applying PSO to routing problems is that the variables are discrete (e.g., a link is either in a route or not), whereas the classic PSO operates in a continuous space. The core of our GT-PSO utilizes the Sig-bo game discretization technique, inspired by the work of Pornsing et al. [9]. This method serves as the particle's strategic decision function, transforming the continuous velocity into a discrete action.

Instead of a direct position update, the velocity update equation (4.1) is calculated. This resulting continuous velocity value is then mapped to a discrete, binary decision for the particle's new position using a set of probabilistic rules based on the Thai dice game "Sig-bo". As detailed in the original report, the velocity update for each dimension j of particle i is calculated based on three acceleration components: its current position $(a_i^{k+1}(x_i^k(j)))$, its personal best $\left(a_i^{k+1}(pbest_i^k(j))\right)$, and the global best $\left(a_i^{k+1}(gbest_i^k(j))\right)$. The sum of these accelerations produces the new velocity, $v_i^{k+1}(j)$. This velocity is then mapped to a binary state based on threshold values derived from the game's rules (10):

$$x_i^{k+1}(j) = \begin{cases} 0 & \text{if } 11 \leq v_i^{k+1}(j) \leq 18 \\ 1 & \text{if } v_i^{k+1}(j) \leq 10 \\ \text{No change} & \text{if } 10 \leq v_i^{k+1}(j) \leq 11 \end{cases} \tag{10}$$

This mechanism provides a structured, probabilistic way to handle the discrete nature of the problem, allowing particles to either switch to a '1' state (include an arc), switch to a '0' state (exclude an arc), or maintain their current

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state. This approach avoids the common pitfalls of other discretization methods and provides a robust exploration-exploitation balance. The pseudocode for the algorithm is presented in Table 1.

Table 1 Pseudocode for the GT-PSO

Step	Description

1	Initialization
	(a) Set $k = 0$.
	(b) Randomly initialize the position of the m particles in binary numbers.
	(c) Randomly initialize the velocity of the m particles in binary numbers.
	    For $i = 1, \dots, m$ do $pbest_i^k = X_i$.
	    Set $gbest^k = \arg \min_{i \in 1, \dots, m} f(X_i)$.

2	Terminate Check. If the termination criteria hold stop. Then, the outcome of the algorithm will be $gbest$.

3	For $i = 1, 2, \dots, m$ do
	Calculating acceleration values.
	    (a) Calculate $a_i^{k+1}(x_i^k(j))$.
	    (b) Calculate $a_i^{k+1}(pbest_i^k(j))$.
	    (c) Calculate $a_i^{k+1}(gbest^k(j))$.
	Updating particle swarm.
	    (a) Update the velocity V_i^k using
	    $v_i^{k+1}(j) = a_i^{k+1}\left(x_i^k(j)\right) + a_i^{k+1}\left(pbest_i^k(j)\right) + a_i^{k+1}(gbest^k(j))$
	    (b) Update the position X_i^k using Eq. (47).
	    $x_i^{k+1}(j) = \begin{cases} 1 & \text{if} \quad 11 < v_i^{k+1}(j) \leq 18 \\ 0 & \text{if} \quad v_i^{k+1}(j) \leq 10 \\ \text{No change if } 10 < v_i^{k+1}(j) \leq 11 \end{cases}$
	Updating $pbest_i$ and $gbest$.
	    (c) If $f(X_i) \leq f(pbest_i)$ then $pbest = X_i$.
	    (d) If $f(pbest_i) \leq f(gbest)$ then $gbest = pbest_i$.
	End For.

4	Set $k = k + 1$.
5	Go to step 2.

Each step of the GT-PSO has been designed to address the unique characteristics of the GIRP. The initialization phase ensures diverse solution exploration, crucial for high-dimensional routing problems. The Sig-bo game discretization introduces a probabilistic mechanism that reflects real-world decision uncertainty while preserving exploration capability. The iterative velocity-position updates simulate adaptive learning among particles, mirroring dynamic interactions in inventory-routing systems. Finally, the update of personal and global best solutions allows continuous refinement toward cost-effective and environmentally responsible logistics plans. These design choices collectively make GT-PSO well-suited to tackle the combinatorial complexity and conflicting objectives inherent in GIRP.

4.3   The proposed algorithm analysis

The complexity of the proposed algorithm can be evaluated in two main categories: Time Complexity, which measures how the runtime scales with the size of the problem, and Space Complexity, which measures the amount of memory required.

4.3.1   Time complexity

The time complexity of the GT-PSO algorithm is primarily determined by the nested loops in its structure and the cost of the fitness function evaluation. The overall structure is (11):

$$Total\ Time = (Max\ Iteration) \times (Number\ of\ Particles) \times (Cost\ per\ Particle\ per\ Iteration) \qquad (11)$$

Let's define the key variables related to the problem size:
n = Number of customers.
H = Number of periods in the planning horizon.
m = Number of vehicles.

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T_{max} = The maximum number of iterations (a user-defined parameter)
N_p = The number of particles in the swarm (a user-defined parameter)

The cost per particle in each iteration consists of three main operations:
1. Velocity and Position Update: These are vector operations with a complexity proportional to the dimension of the solution vector, D. This is a relatively fast operation.

Fitness Function Evaluation ($f(X_i)$): This is the most computationally intensive step. To evaluate the fitness of one particle (a complete solution), the algorithm must calculate the total cost over the entire planning horizon.
- Routing & Emission Cost: This involves decoding the particle's position to determine the routes for m vehicles over H periods, visiting up to n customers. The complexity is approximately $O(H \times m \times n)$.
- Inventory Cost: This requires calculating the inventory level for n customers over H periods, which has a complexity of $O(n \times H)$.
- Therefore, the complexity of the fitness function is dominated by the routing calculation, making it $O(H \times m \times n)$.

2. Best Solution Update: Comparing the new solution's cost to $pbest$ and $gbest$ is a constant time operation, $O(1)$. Combining these factors, the fitness evaluation is the clear bottleneck. The total time complexity is (12):

$$Time\ Complexity = O(T_{max}N_pHmn) \qquad (12)$$

This shows that the algorithm's runtime scales polynomially with the primary dimensions of the problem: the number of customers, periods, and vehicles.

4.3.2 Space complexity
Space complexity refers to the memory needed to store the data structures used by the algorithm during its execution. The main components are:
Swarm Data: The algorithm must store the state for every particle in the swarm. For each of the N_p particles, this includes:
Position vector (X_i)
Velocity vector (V_i)
Personal best position vector ($pbest_i$)
Global Data: A single global best position vector ($gbest$) is stored for the entire swarm.
Problem Data: Memory is also needed to store the problem instance itself, such as the distance matrix between customers, which is $O(n^2)$.

The dominant factor in the algorithm's memory usage is the swarm data. If the dimension of the solution vector for a single particle is D, the space complexity is (13):

$$Space\ Complexity = O(N_pD) \qquad (13)$$

The dimension D depends on the solution encoding scheme. It is a function of the problem parameters (n, H, m), as it must contain enough information to represent a full delivery and routing plan.
In summary, the proposed GT-PSO algorithm has a pseudo-polynomial time complexity that is highly dependent on the user-defined number of iterations and particles, and it scales polynomially with the problem's dimensions within each iteration. Its space complexity is linear with respect to the swarm size and the dimension of the solution representation.

5 Computational experiments and results
5.1 Experimental setup
The proposed PSO for GIRP was coded in C++ and executed on a machine with an Intel Core i7-8750H CPU @ 2.20 GHz and 8.0 GB of RAM. A termination time limit of 3,600 seconds was set for each run.
- Benchmark Problems: Thirteen benchmark instances were adapted from Moin et al. (2011) and Shaabani and Kamalabadi (2016). They are categorized as small (12 customers), medium (20-50 customers), and large (98 customers), with varying planning horizons (5, 10, 14, 21 periods). Details are provided in Table 2.
- Competitive Algorithms: The performance of our PSO for GIRP was compared against a standard Genetic Algorithm (GA), Simulated Annealing (SA), and the commercial MILP solver Gurobi.
- Parameter Tuning: The parameters for all metaheuristics were carefully tuned using a standard instance (S12T14M) to ensure a fair comparison. The key parameters for PSO for GIRP include an inertia weight (ω) decreasing from 0.65 to 0.20, acceleration constants (ϕ_1, ϕ_2) of 1.5, and a population of 100 particles.

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- Performance Evaluation: To assess solution quality, we calculated the integrality gap using the best upper bound (z_{ub}) found by the algorithms and a strong lower bound (z_{lb}) obtained from the better of two methods: Lagrangian relaxation and Linear Programming (LP) relaxation. The gap is calculated as (Table 2):

Table 2 Summary of benchmark problem characteristics

Problem set	No. customer	No. periods	Size category
S12T5M - S12T14M	12	5-14	Small
S20T5M - S50T14M	20-50	5-21	Medium
S98T5M - S98T14M	98	5-14	Large

5.2 Computational results

The comprehensive results of our computational experiments are summarized in Table 3. For each problem instance, the table shows the best objective function value obtained by each upper-bound method (Gurobi, GA, SA, and PSO for GIRP) and the final integrality gap based on the best lower bound found.

Table 3 Computational results for upper bound methods and overall gap

Problem Set	Gurobi	GA	SA	GT-PSO	Overall Gap* (%)
S12T5M	113.5	119.6	115.4	113.5	0.71
S12T10M	215.4	219.6	217.6	215.5	0.42
S12T14M	675.3	683.2	701.8	675.3	0.75
S20T5M	4453.1	4518.2	4590.2	4458.2	0.86
S20T10M	5207.5	5207.9	5334.8	5221.3	0.37
S20T14M	9191.6	9185.4	9355.9	9178.3	0.59
S20T21M	NA	10475.8	10832.4	10443.8	0.47
S50T5M	NA	50211.6	51425.3	50190.1	0.20
S50T10M	NA	120548.2	122473.5	120485.9	0.08
S50T14M	NA	210368.5	211971.5	210219.7	0.18
S98T5M	NA	753098.4	756301.5	75188.9	-
S98T10M	NA	923931.7	924015.2	920157.8	-
S98T14M	NA	1342781.2	1401842.3	1315043.6	-

Note: NA indicates Gurobi could not find a feasible solution within the 3,600s time limit. The best solution for each instance is in bold. Gaps for large instances could not be calculated as no lower bound was found in time.

5.3 Analysis and discussion

The results clearly highlight the strengths and weaknesses of each approach.

5.3.1 Performance comparison

For small-sized instances, Gurobi successfully found the optimal or near-optimal solutions within the time limit, outperforming the metaheuristics as expected. Our PSO for GIRP matched Gurobi's performance on two of these instances. However, for all medium- and large-sized instances, Gurobi failed to produce a solution in time. In this critical domain, the proposed PSO for GIRP consistently and significantly outperformed both GA and SA, finding the best-known solution in every single case. The integrality gap for our method remained below 0.97% across all solvable instances, demonstrating the high quality of the solutions obtained.

Figure 1 compares the best objective function values (lowest total cost) achieved by the Genetic Algorithm (GA), Simulated Annealing (SA), and the proposed GT-PSO for medium- and large-sized problem instances.

The visual evidence is compelling. For every instance shown, the green bar representing the proposed GT-PSO is the lowest, indicating a superior solution quality. The performance gap between GT-PSO and the other two algorithms widens as the problem size increases (e.g., in problems S98T10M and S98T14M), demonstrating the robustness and scalability of the proposed method in handling complex, large-scale green logistics scenarios.

These results empirically confirm that the integration of game-theoretic logic into PSO significantly enhances search efficiency and solution stability. The adaptive probabilistic decision rule allows particles to maintain a balanced exploration–exploitation trade-off, preventing stagnation and enabling discovery of near-optimal routes even in high-dimensional solution spaces. From an academic perspective, this supports the theoretical proposition that game-based interactions can improve swarm intelligence algorithms' performance on discrete optimization tasks. For practitioners, the findings suggest that implementing GT-PSO in logistics planning software could lead to tangible reductions in operational costs and emissions without requiring additional computational resources.

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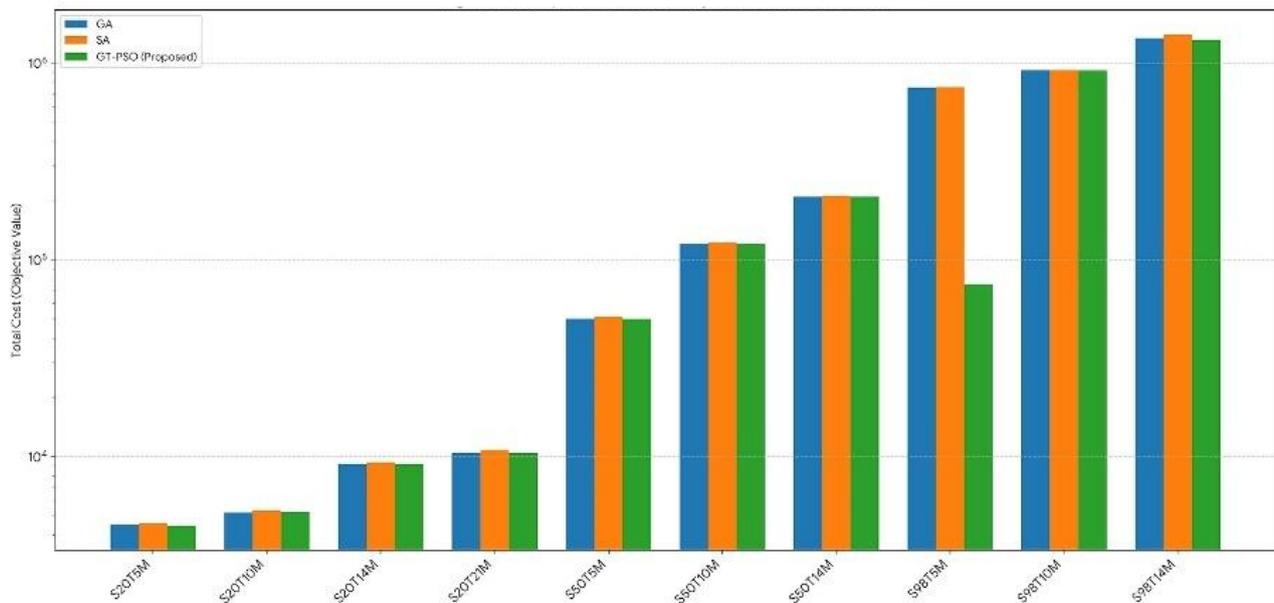
Figure 1 Comparison of best objective function values

5.3.2   Statistical analysis

An Analysis of Variance (ANOVA) was conducted on the results for small- and medium-sized problems to test for significant differences between the three metaheuristics. The results (F-value = 3.99, p-value = 0.0368) show a statistically significant difference in performance at a 95% confidence level. A subsequent Tukey HSD post-hoc test revealed that all pairwise comparisons were significant, confirming that PSO for GIRP's performance is not just numerically better but statistically superior to both GA and SA.

5.3.3   Consistency analysis

To evaluate the reliability of the algorithms, we analyzed the Coefficient of Variation (CV) of the objective function values over multiple runs for representative problems. As shown in Table 4, the proposed PSO for GIRP consistently exhibited the lowest CV, particularly for the large-sized instance (7.55% vs. 8.89% for GA and 9.59% for SA). This indicates that our method is not only more effective but also more consistent and reliable in its performance.

Figure 2 illustrates the consistency of the three metaheuristics by comparing their Coefficient of Variation (CV) across small, medium, and large representative problem instances. A lower CV value signifies greater reliability and less variance in solution quality over multiple runs.

Table 4 Coefficient of variation (CV) for a large-sized instance (S98T14M)

Method	Mean	Std. Deviation	CV (%)
GA	86,784.88	7,717.42	8.89%
SA	86,471.64	8,296.31	9.59%
GT-PSO	**88,198.88**	**6,661.75**	**7.55%**

The proposed GT-PSO (green bar) consistently exhibits the lowest CV across all problem scales. This demonstrates its superior stability and reliability. While other algorithms might produce a good result occasionally, the proposed method dependably delivers high-quality solutions. This is a crucial attribute for practical deployment in real-world planning systems where consistent performance is essential.

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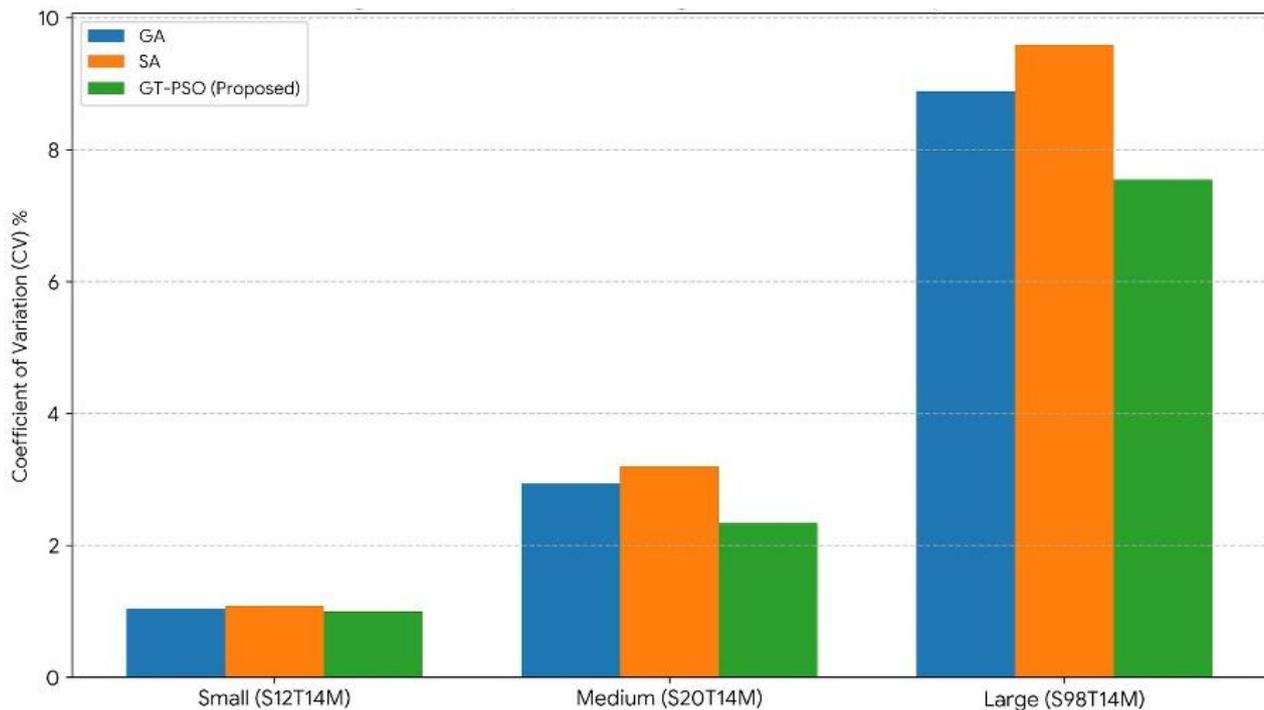
Figure 2 Comparison of algorithm consistency (coefficient of variation)

5.3.4   Convergence behaviour

The convergence plots (Figure 3) illustrate the search dynamics. The plot highlights distinct search behaviors. The GA (blue line) shows rapid initial improvement but quickly flattens, indicating premature convergence to a local optimum. In contrast, the GT-PSO (green line) demonstrates a steady and continuous improvement, effectively avoiding stagnation. This superior balance of exploration (searching broadly) and exploitation (refining good solutions) allows it to navigate the complex search space more efficiently and ultimately discover better final solutions.

Figure 4 compares the execution time (in seconds) required by each metaheuristic to complete its run for problem instances of increasing size and complexity.

The graph confirms that all three metaheuristics have comparable computational runtimes, with all methods scaling polynomially as the problem size increases. There is no significant and systematic time advantage for any single algorithm. This is a critical finding, as it demonstrates that the superior solution quality of the proposed GT-PSO is not achieved at the expense of longer computational time. The key differentiator is the efficiency of the search algorithm itself, not the raw processing time.

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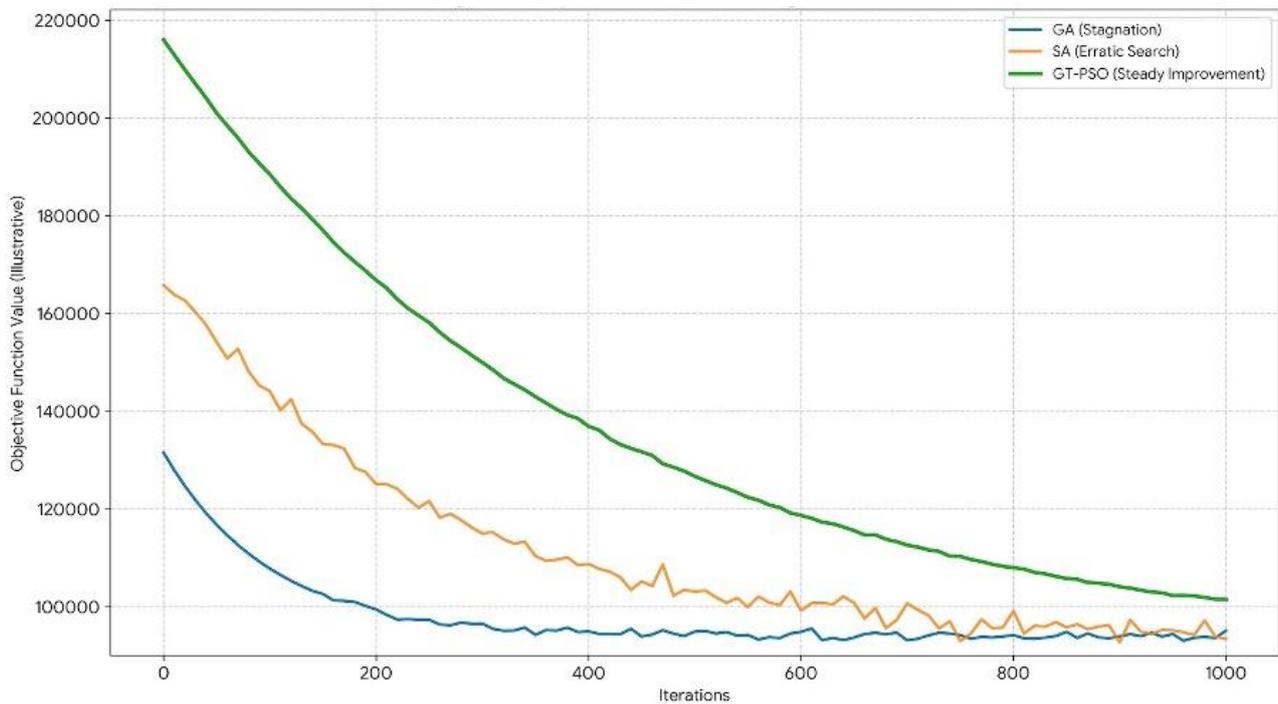
Figure 3 Representative convergence behaviour
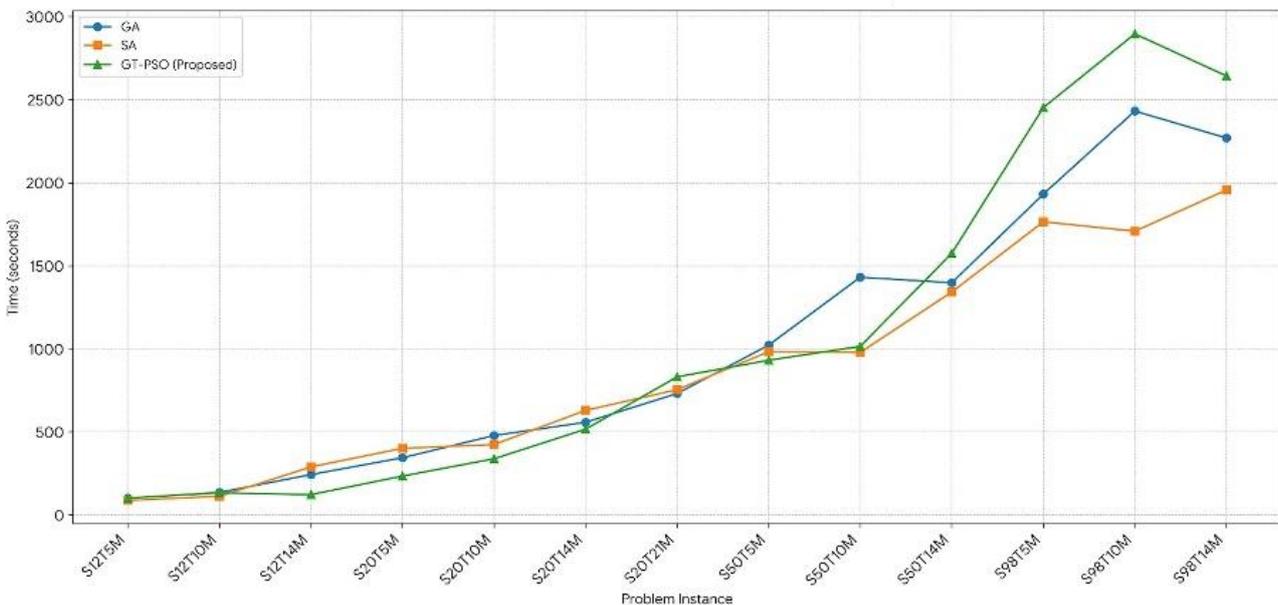
Figure 4 Comparison of computational time

6   Conclusion and future work

This research advances logistics system optimization by integrating game-theoretic reasoning into swarm-based metaheuristics, enabling more efficient management of material and transport flows in sustainable distribution networks. The research successfully developed and validated a novel Game-Theoretic Particle Swarm Optimization (GT-PSO) for the Green Inventory Routing Problem. By conceptualizing the critical discretization step as a strategic game, our method demonstrated superior performance in solving this complex optimization challenge. The two primary objectives of the study were achieved: we proposed an improved metaheuristic, the GT-PSO, and we demonstrated its superior performance through extensive computational experiments.

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The key conclusion of this work is that the proposed GT-PSO is a highly effective and robust tool for solving large-scale, real-world GIRP instances. It consistently outperformed both Genetic Algorithm and Simulated Annealing in terms of solution quality, statistical significance, and consistency, especially as problem complexity increased. The novel game-theoretic discretization strategy proved to be a powerful mechanism, enabling the algorithm to effectively navigate the discrete solution space and avoid the common pitfalls of premature convergence.

The novelty of this approach lies not only in integrating game theory into PSO but also in demonstrating its consistent superiority across diverse benchmark instances. This game-theoretic framework can be generalized to other NP-hard sustainability-related optimization problems, making it a special and versatile contribution to green operations research.

Managerial Implications: For logistics and supply chain managers, this research provides a practical and powerful decision-support tool. The model's ability to integrate and weigh economic and environmental costs offers the flexibility to adapt to different regulatory environments (e.g., varying carbon taxes) and corporate sustainability goals. By using this algorithm, companies can design distribution strategies that not only minimize operational costs but also significantly reduce their carbon footprint, thereby achieving a competitive advantage in an increasingly eco-conscious market.

Practically, the results provide logistics managers with a tool capable of handling large-scale, environmentally constrained routing decisions. Academically, the work contributes to the growing literature on hybrid intelligent optimization by illustrating how behavioural decision models—like game theory—can enhance classical swarm-based algorithms.

Limitations and Future Work: While this study provides a strong foundation, it has certain limitations that open avenues for future research. The model assumes deterministic parameters; future work could explore stochastic GIRP by incorporating uncertainty in demand or travel times. Another promising direction is to reformulate the problem as a true multi-objective optimization problem and use techniques like Pareto optimization to find a set of non-dominated solutions, giving decision-makers a range of trade-offs rather than a single point solution. Further research could also investigate heterogeneous fleets including electric vehicles (EVs) and develop more sophisticated emission models. Finally, applying and validating the proposed algorithm on a real-world industry case study would be an invaluable next step to confirm its practical utility.

Acknowledgement

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Barriers to green manufacturing implementation in industrial enterprises

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Keywords: green manufacturing, barriers of green manufacturing, industrial enterprises.
Abstract: The paper analyses barriers to the implementation of green manufacturing in industrial enterprises in Slovakia, focusing on financial, technological, and organizational barriers. Based on a questionnaire survey, the main obstacles were identified, including insufficient investment, a lack of skilled labour, and limited access to green resources. To evaluate regional and size-related differences, the Chi-square test was applied to determine whether the occurrence of barriers varies according to the geographical location or size of the enterprise. The results of the analysis did not show statistically significant differences between regions in Slovakia or between enterprise size categories, indicating that the barriers to implementing green manufacturing have a nationwide character. However, the most frequent barriers were found to be insufficient financial resources, a shortage of qualified employees, and limited availability of raw materials and technological infrastructure. These factors negatively affect the eco-innovation performance of enterprises, reducing their ability to implement green manufacturing principles and respond effectively to identified barriers. A comparison with the Eco-Innovation Index 2024 further confirmed Slovakia's below-average performance within the European Union, highlighting insufficient investment in eco-innovation, weak cooperation between the public and private sectors, and limited government support. The findings suggest that overcoming these obstacles requires the development of targeted financial mechanisms, stronger institutional support, and the integration of environmental training programs for employees. This paper aims to identify the main barriers to the implementation of green manufacturing in industrial enterprises in Slovakia and to analyse their differences between regions and individual enterprise size categories.

1   Introduction

Green manufacturing is an approach that focuses on minimizing the negative environmental impacts of manufacturing, optimizing material flows, and maintaining or improving economic efficiency. This concept includes technologies and practices such as waste reduction, energy savings, and the use of renewable resources [1]. In recent years, there has been growing pressure on industrial enterprises to implement more environmentally friendly solutions, driven by increasing environmental regulations, social requirements, and need for sustainability [2].

Despite the clear advantages of green strategies, many enterprises encounter financial, technological, and organizational barriers that hinder their implementation in manufacturing processes. Several studies confirm that the most significant barriers include a lack of investment, skilled workers, insufficient management support, and ineffective supplier relationships [1,3], which lead to limited availability of green materials and technologies [4].

These factors have a fundamental impact on enterprises' decisions to switch to green manufacturing and can significantly slow down the ecological transformation of industry.

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The most common barriers to the implementation of green manufacturing and its approaches are:

1. **Lack of initial investment**

One of the most frequently identified barriers to implementation of green manufacturing is a lack of initial investment resources. Enterprises, especially small and medium-sized ones, often struggle with uncertainty about the return on investment of green projects [5], which discourages them from introducing green technologies. Investments in green solutions such as green hydrogen, green IT systems, and green supply chains are capital-intensive [6]. Financial barriers are further compounded by the unavailability of public or private investment inducements [7,8].

2. Lack of qualified employees

The green transition requires new skills, particularly in the areas of digital technologies, environmental management, and the circular economy, as well as expertise in the technical aspects of logistics and information flow management. However, many enterprises face a shortage of workers with the relevant skills [9,10]. In addition, there is a lack of systematic training programs and incentives to build a green culture within work teams [8,11]. The introduction of a cross-disciplinary approach that also integrates green manufacturing within Industry 4.0 and 5.0 requires trained personnel capable of adapting to process changes [12].

3. Insufficient support from top management

Lack of interest or weak awareness among top management about the importance of green manufacturing is one of the key obstacles to progress [13]. The transition to sustainable manufacturing systems requires not only a decision by enterprise management but also active support in the form of a vision, internal policies, and investment in human capital flow [14]. Especially in small enterprises, the environmental agenda is often subordinated to short-term goals [15].

4. Nonoptimal supplier relationships

Cooperation in supply chains and effective supply chain management are important for the environmental optimization of the entire manufacturing cycle. However, if suppliers are not involved in the green strategy, inconsistencies and risks are raised [14]. Problems also stem from a lack of trust, poor communication, and a lack of technical know-how among partners [16,17].

5. Lack and availability of resources

The introduction of green manufacturing requires access to suitable raw materials, renewable energy sources, physical infrastructure, and data. A lack of these capacities often obstructs progress [18]. In addition to physical resources, the availability of high-quality environmental data is also important, but this is limited in many enterprises [8,19].

6. Resistance to implementing new technologies

Innovations such as green manufacturing cells, digital twins, and intelligent energy optimization are among the key elements of effective sustainability, but their implementation is often slowed by a lack of trust and the risk of disrupting stable manufacturing [20]. Enterprises fear technological incompatibility between existing and new systems, as well as a loss of competitiveness in the event of failure [8].

7. Deficiencies in organizational structure

Organizational barriers, such as excessive hierarchy, slow decision-making, or unclear responsibilities, significantly affect the effectiveness of environmental measures [2,21]. The transformation towards green manufacturing requires more flexible structures with a focus on teamwork, accountability, process agility, and the interconnection of manufacturing, distribution, and information flows [22].

8. Insufficient government support

Public policies have a fundamental impact on the pace of transformation of manufacturing enterprises. Insufficient legislative certainty, weak regulatory measures, a lack of stimulus, and low environmental awareness slow down green transformations [8]. Enterprises expect clear guidance from the state, not only in the form of standards, but also in the areas of infrastructure, research, and financing that support green manufacturing and green logistics, as well as ecologically optimized material and information flows [6,7].

Several studies confirm that the region in which an enterprise operates, and the size of the enterprise are among the key factors influencing the ability of enterprises to implement green innovations and sustainable manufacturing approaches. Large enterprises often have better access to technology, finance, and innovation, which enables them to implement environmental measures more effectively. Conversely, smaller enterprises face greater financial and personnel limitations, which can hamper their ability to implement green strategies [23,24].

Geographical factors, such as location within a country or region, influence the availability of infrastructure, the regulatory environment, and market conditions. Enterprises in economically stronger regions or areas with more developed infrastructure are better placed to implement green innovations due to their greater access to finance and innovation [23,25]. At the same time, it appears that the effectiveness of environmental policies and their impact on enterprises varies according to local socio-technical systems and regional characteristics [23,26].

This paper aims to identify the main barriers to the implementation of green manufacturing in industrial enterprises in Slovakia and to analyse their differences between regions and individual enterprise size categories.

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The paper also compares the situation in Slovakia with other European Union countries based on the Eco-Innovation Index 2024, providing a broader view of the issue and allowing for the identification of common and specific challenges in different economic contexts.

2 Methodology

The first step of the research was to process the theoretical foundations of the issue based on scientific contributions selected according to their relevance and year of publication. Preference was given to contributions published in the last decade that focused on the issue of barriers to green manufacturing in industrial enterprises. The overview of the professional literature thus obtained provided a basis for formulating research questions, hypotheses, a questionnaire, data collection, and subsequent analysis of the results.

Research questions (RQ):

RQ1: What barriers to the implementation of green manufacturing are most identified by industrial enterprises in Slovakia?

RQ2: What barriers to the implementation of green manufacturing are most identified in small and medium-sized enterprises and which in large enterprises in Slovakia?

Research hypotheses (RH):

RH1 (regions): There are differences between Slovak regions in terms of the identified barriers to the implementation of green manufacturing in industrial enterprises.

RH2 (enterprise size): There are differences between enterprises of different sizes in the barriers identified to the implementation of green manufacturing in industrial enterprises.

The research was conducted through a questionnaire survey in industrial enterprises in Slovakia, with respondents answering questions about the geographical location of the enterprise, its size category, and the identification of the main barriers to the implementation of green manufacturing principles.

The research was conducted using an online questionnaire, and the collected data were processed in MS Excel and analysed using Spyder 5.5.1 software. The research for this paper aimed to determine the current state of identified barriers to the implementation of green manufacturing, whether there is a statistically significant difference in the presence of barriers between regions of Slovakia, and whether there is a difference in the identified barriers to green manufacturing between enterprises according to size classification. To verify regional differences and differences between size categories of industrial enterprises, a chi-square analysis was used to test statistically significant differences in the presence of barriers between regions of Slovakia and between size categories of industrial enterprises. The results of the research are presented graphically and in tables.

An anonymous questionnaire was distributed to industrial enterprises in the Slovak Republic. The respondents to the questionnaire survey were selected enterprises from the "C industrial manufacturing" group that conduct enterprise activities in Slovakia, and their number as of December 31, 2023, was 30,020 in total. According to the SK NACE classification under the following numerical codes and names (SK NACE is an abbreviation for the Statistical Classification of Economic Activities in the Slovak Republic, which is the national version of the European NACE Rev. 2 classification), categories 23, 24, 25, 26, 27, 28, 29, 30, and 32 were included in the analysis. Different enterprises may have multiple SK NACE classifications depending on their activities. We sent the questionnaire to energy and material-intensive industrial enterprises that have a significant environmental impact and are subject to strict environmental regulations. Given the high levels of emissions, waste, and raw material consumption, green manufacturing is essential to ensure sustainability in these sectors. The questionnaire wasn't distributed to other sectors because non-manufacturing sectors and light industry do not have as significant an environmental impact as the selected industrial categories. We sent the questionnaire to 750 industrial enterprises, representing 2.5% of the total sample of 30,020 industrial enterprises. The survey lasted two months. By the last day of data collection (February 29, 2024), a total of 88 respondents had completed the questionnaire, meaning that the response rate was 11.4%. We approached employees from the following areas of activity: environmental department, occupational health and safety department, quality and sustainability department, development and innovation department, purchasing and logistics department, manufacturing and technical department, and senior management. The sample of responding enterprises was divided according to EU Recommendation 2003/361/EC based on the number of employees. The resulting values for each size category are shown in Table 1.

Table 1 Distribution of enterprises by number of employees in absolute and relative terms

	Absolute frequency	Relative frequency
Micro enterprises / up to 10 employees	10	11.36%
Small enterprises / up to 50 employees	23	26.14%
Medium enterprises / up to 250 employees	37	42.05%
Large enterprises / more than 250 employees	18	20.45%

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The largest representation in the survey is the group of medium-sized enterprises, followed by the group of small enterprises. The enterprises were also divided according to their geographical location into individual regions of the Slovak Republic, as shown in Figure 1. The largest representation of manufacturing enterprises is from the Trenčín, Bratislava, and Trnava regions.

Figure 1 Representation of enterprises from individual regions in absolute numbers

Geographical factors can influence the intensity of barriers to green manufacturing implementation in Slovakia's industrial enterprises. Enterprises in economically stronger regions, such as the Bratislava region, may have better access to financing and skilled labour, which allows them to overcome obstacles for easier implementation of green solutions. Conversely, in regions with lower economic performance, such as the Prešov and Banská Bystrica regions, the dominant barriers may be a lack of investment, limited technological infrastructure, and a shortage of skilled workers.

To verify regional differences in the presence of financial, technological, organizational, and legislative barriers, a chi-square analysis was applied to test statistically significant differences in their frequency between regions.

To verify both hypotheses, individual barriers (lack of initial investment, lack of skilled workers, unavailability of resources, resistance to new technologies, shortcomings in organizational structure, insufficient support from management, suboptimal relationships with suppliers, and insufficient state support) were tested separately and collectively using the chi-square test.

The chi-square test compares the observed and expected frequencies of barriers in individual regions and determines whether the differences between them are random or statistically significant.

The P-value is used to decide on the statistical significance of differences at a chosen significance level of $\alpha = 0.05$.

The results of this analysis provide an overview of regional differences and differences in enterprise size in terms of barriers to green manufacturing and enable the identification of specific factors influencing the implementation of green solutions in individual regions of Slovakia and in enterprises according to size.

The analysis also focused on comparing the situation in Slovakia in terms of introducing eco-innovations into the economy, manufacturing, and consumption with other European Union countries based on the Eco-Innovation Index 2024, thus providing a broader view of the issue and enabling the identification of common and specific challenges in different economic contexts. The results of the research, which analyse regional and size differences between enterprises in identifying these barriers, provide an overview of the barriers to the implementation of green manufacturing in industrial enterprises in Slovakia.

3   Results and discussion

One of the results of the analysis conducted through a questionnaire survey in Slovakia is that the selected barriers generally present in several economies around the world, which we describe in the "Introduction" section, are also faced by enterprises in Slovakia.

Result 1 - RQ1: What barriers to the implementation of green manufacturing are most identified ***by industrial enterprises in Slovakia?***

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Figure 2 shows the absolute frequency of individual barriers encountered by industrial enterprises in Slovakia in their practice. Respondents could select multiple options for each question.
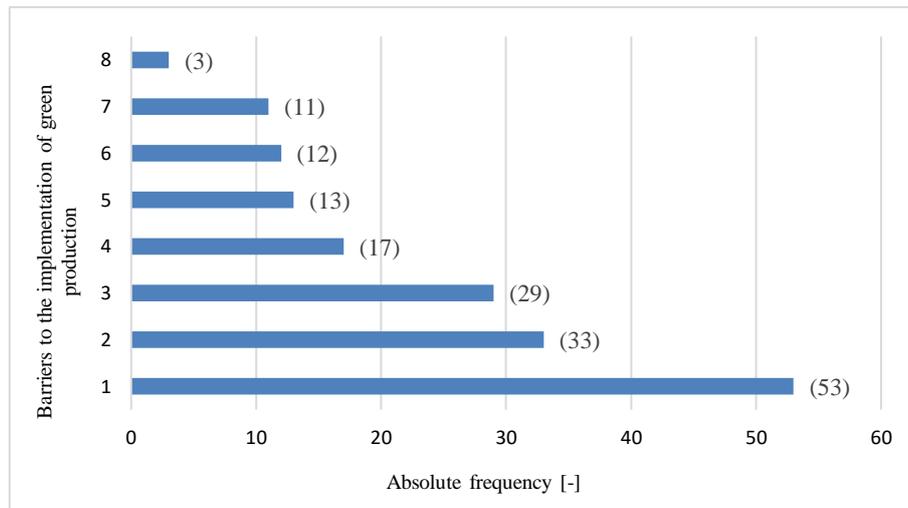

Figure 2 Absolute frequency of responses regarding existing barriers

Legend: (The same legend applies to Table 2 and Table 4)
1. Lack of initial investment (most significant barrier)
2. Lack of qualified employees
3. Lack and availability of resources
4. Resistance to implementing new technologies
5. Deficiencies in organizational structure
6. Insufficient support from top management
7. Suboptimal supplier relationships
8. Insufficient government support (least significant barrier)

The most significant obstacle is the lack of initial investment, which was identified as the main problem by 53 of the 88 respondents (60.2%). The lack of qualified employees is the second most frequently cited barrier, with 33 industrial enterprises (37.5%) involved in the survey facing a shortage of green technology experts. The lack of resources and their availability make it difficult for 29 industrial enterprises (33%) to obtain environmentally friendly materials, which is also reflected in the disruption of supply and demand flows and the availability of suitable means of transport necessary to ensure continuity of manufacturing. The rejection of new technologies is a problem for 17 industrial enterprises involved in the survey, which points to a low willingness to invest in innovation due to high costs and uncertainty of return. Organizational barriers and weak support from top management reflect a lack of strategy in the area of green measures. Inefficient supplier relationships signal problems in securing green components, which affects manufacturing efficiency. The least significant obstacle insufficient government support indicates that enterprises perceive internal factors as a greater barrier than insufficient government support.

Result 2 – RQ2:   What barriers to the implementation of green manufacturing are most identified in small and medium-sized enterprises and which in large enterprises in Slovakia?

We analysed the presence of barriers encountered by industrial enterprises in Slovakia, focusing on the size classification of enterprises and examining barriers in individual categories of industrial enterprises according to size. A specific comparison is shown in Figure 3.

Key findings:

• The most significant barrier in all categories is the lack of initial investment, which affects micro enterprises the most. Its impact decreases slightly as the size of the enterprise increases, but it remains a dominant factor even in medium-sized and large enterprises.

• The lack of skilled employees and limited availability of raw materials are key barriers in medium and large enterprises. This trend suggests that as the scale of manufacturing increases, so do the demands for skilled labour and material supplies flow.

• The rejection of new technologies and organizational limitations are present to a similar extent across all size categories, suggesting that these are systemic barriers not directly related to the size of the enterprise.

• Insufficient support from top management and ineffective supplier relationships are a problem across all categories, with the most significant impact on medium-sized enterprises. This may be related to their transition between small and large enterprises, where they face higher demands for supply chain management and coordination.

• Insufficient support from the state is the least significant barrier in all categories, suggesting that enterprises perceive other factors - particularly financing and human resources - as more important for implementing green manufacturing.

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• Small, medium-sized, and large enterprises most frequently encountered the same barriers: lack of initial investment, lack of skilled employees, and limited availability of raw materials.
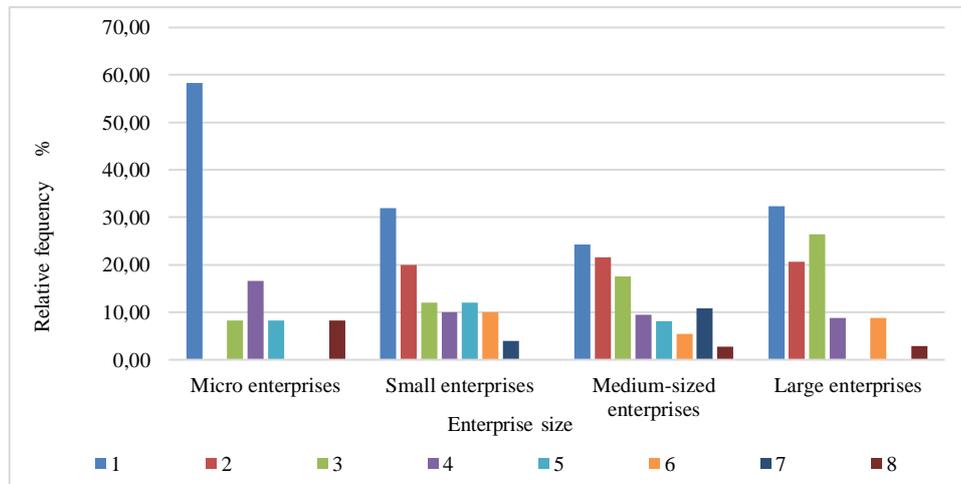
Figure 3 Barriers to the implementation of green manufacturing in industrial enterprises by size category in Slovakia

Legend:
1. Lack of initial investment (most significant barrier)
2. Lack of qualified workers
3. Lack and availability of resources
4. Resistance to implementing new technologies
5. Deficiencies in organizational structure
6. Insufficient support from top management
7. Suboptimal supplier relationships
8. Insufficient government support (least significant barrier)

Result 3 - RH1 (regions): There are differences between Slovak regions in the identified barriers to the implementation of green manufacturing in industrial enterprises.

The frequency of responses is shown in Table 2. For the purposes of evaluating research hypothesis 1, responses from the research questionnaire were compared.

Table 2 Barriers to the implementation of green manufacturing in individual regions

Barriers to the implementation of green manufacturing /Region	1	2	3	4	5	6	7	8	Total
Trencin Region	13 (59.1%)	4 (18.2%)	7 (31.8%)	3 (13.6%)	3 (13.6%)	4 (18.2%)	0 (0.0%)	0 (0.0%)	22 (100%)
Bratislava Region	7 (53.8%)	5 (38.5%)	4 (30.8%)	2 (15.4%)	2 (15.4%)	1 (7.7%)	5 (38.5%)	0 (0.0%)	13 (100%)
Trnava Region	8 (66.7%)	6 (50.0%)	5 (41.7%)	4 (33.3%)	2 (16.7%)	2 (16.7%)	2 (16.7%)	2 (16.7%)	12 (100%)
Banska Bystrica Region	4 (36.4%)	5 (45.5%)	6 (54.5%)	3 (27.3%)	3 (27.3%)	0 (0.0%)	1 (9.1%)	0 (0.0%)	11 (100%)
Presov Region	4 (44.4%)	5 (55.6%)	1 (11.1%)	3 (33.3%)	2 (22.2%)	1 (11.1%)	0 (0.0%)	1 (11.1%)	9 (100%)
Zilina Region	8 (100.0%)	3 (37.5%)	2 (25.0%)	1 (12.5%)	0 (0.0%)	2 (25.0%)	2 (25.0%)	0 (0.0%)	8 (100%)
Nitra Region	4 (57.1%)	2 (28.6%)	2 (28.6%)	1 (14.3%)	1 (14.3%)	1 (14.3%)	1 (14.3%)	0 (0.0%)	7 (100%)
Kosice Region	5 (83.3%)	3 (50.0%)	2 (33.3%)	0 (0.0%)	0 (0.0%)	1 (16.7%)	0 (0.0%)	0 (0.0%)	6 (100%)
∑Sum	53 (60.2%)	33 (37.5%)	29 (33.0%)	17 (19.3%)	13 (14.8%)	12 (13.6%)	11 (12.5%)	3 (3.4%)	88 (100%)

To verify whether there are regional differences in the identification of barriers to the implementation of green manufacturing, a chi-square test of independence was used. The hypothesis tested was that the occurrence of individual

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barriers is evenly distributed among the regions of Slovakia and is not influenced by the geographical environment. Table 3 presents the results of separate tests for each barrier, showing the chi-square test statistics, degrees of freedom, and corresponding p-values.

Table 3 Results of the chi-square test for the relationship: region/ barriers to the implementation of green manufacturing

Pearson's Chi-Square Tests			
Barrier	**χ²**	**df**	**p-hodnota**
1. Lack of initial investment	6.423	7	0.491
2. Lack of qualified employees	2.815	7	0.902
3. Lack and availability of resources	7.485	7	0.380
4. Resistance to implementing new technologies	3.545	7	0.831
5. Deficiencies in organizational structure	3.982	7	0.782
6. Insufficient support from top management	4.062	7	0.773
7. Suboptimal supplier relationships	**14.455**	**7**	**0.044**
8. Insufficient government support	5.360	7	0.616
Overall (all barriers combined)	38.546	49	0.846

Overall testing did not reveal any statistically significant differences between enterprises in different regions in terms of their perception of barriers ($\chi^2 = 38.55$; df = 49; p = 0.846). This means that an enterprise's regional affiliation does not significantly influence the overall pattern of identified barriers to the implementation of green manufacturing. Subsequently, differences between regions were examined for each barrier separately. The results of chi-square tests showed that in most cases the differences between regions of Slovakia are not statistically significant. P-values were higher than 0.05 in all cases, except for one barrier. A statistically significant difference was confirmed for the barrier suboptimal relationships with suppliers ($\chi^2 = 14.455$; df = 7; p = 0.044). This means that enterprises in different regions of Slovakia perceive this barrier to the implementation of green manufacturing differently, which may indicate differences in the structure of supply chains and regional enterprises conditions. Other barriers achieved p-values significantly higher than 0.05, indicating that their perception is relatively consistent across regions. A more detailed analysis showed that the Bratislava region reported more significant problems with supplier relationships. In contrast, this barrier was not reported at all in the Trencin, Presov, and Košice regions. These results suggest that regional specifics of the enterprise environment may in some cases influence the intensity of individual barriers, especially those related to the supply chain.

Despite these differences, global testing of the overall dependence between regions and all barriers did not reveal a statistically significant association. This means that the regional environment as a whole is not a key factor in identifying barriers to green manufacturing in Slovakia.

Result 4 - RH2 (enterprise size): There are differences between enterprises of different sizes in the identified barriers to the implementation of green manufacturing in industrial enterprises.

We analysed the presence of barriers encountered by industrial enterprises in Slovakia, focusing on the size classification of enterprises and examining whether there is a difference in the presence of barriers between different size categories of enterprises. The frequency of responses is shown in Table 4. For the purposes of evaluating research hypothesis 2, responses from the research questionnaire were compared.

Table 4 Barriers to the implementation of green manufacturing in individual categories of enterprises

Barriers to the implementation of green manufacturing / Categories of enterprises	1	2	3	4	5	6	7	8	Total
Large Enterprises	11 (61.1%)	7 (38.9%)	9 (50.0%)	3 (16.7%)	0 (0.0%)	3 (16.7%)	0 (0.0%)	1 (5.6%)	18 (100%)
Medium Enterprises	18 (48.6%)	16 (43.2%)	13 (35.1%)	7 (18.9%)	6 (16.2%)	4 (10.8%)	8 (21.6%)	2 (5.4%)	37 (100%)
Small Enterprises	16 (69.6%)	10 (43.5%)	6 (26.1%)	5 (21.7%)	6 (26.1%)	5 (21.7%)	2 (8.7%)	0 (6.5%)	23 (100%)
Micro Enterprises	8 (80.0%)	0 (0.0%)	1 (10.0%)	2 (20.0%)	1 (10.0%)	0 (0.0%)	1 (10.0%)	0 (0.0%)	10 (100%)
∑Sum	53 (60.2%)	33 (37.5%)	29 (33.0%)	17 (19.3%)	13 (14.8%)	12 (13.6%)	11 (12.5%)	3 (3.4%)	88 (100%)

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The chi-square test of independence was applied to identify possible differences between barriers to the implementation of green manufacturing depending on the size of the enterprises. Hypothesis 2 was tested. The table (Table 5) shows the results of separate tests for each barrier, namely the value of the test statistics, the number of degrees of freedom, and the corresponding p-value.

Table 5 Results of the chi-square test for the relationship: enterprise size/barriers to implementation of green manufacturing

Pearson's Chi-Square Tests			
Barrier	χ^2	**df**	**p-hodnota**
1. Lack of initial investment	4.790	3	0.188
2. Lack of qualified workers	3.102	3	0.376
3. Lack and availability of resources	2.911	3	0.406
4. Resistance to implementing new technologies	1.634	3	0.652
5. Deficiencies in organizational structure	2.447	3	0.485
6. Insufficient support from top management	1.558	3	0.669
7. Suboptimal supplier relationships	5.220	3	0.156
8. Insufficient government support	1.231	3	0.746
Overall (all barriers combined)	22.050	21	0.399

Overall testing did not reveal any statistically significant differences between enterprises of different sizes in their perception of barriers ($\chi^2 = 22.050$; df = 21; p = 0.399). This means that the size category of an enterprise is not a decisive factor in identifying barriers to the implementation of green manufacturing. Subsequently, the differences between enterprises for each barrier were analysed separately. The results showed that none of the barriers were statistically significantly different between enterprise size categories (all p-values > 0.05). The barriers that came closest to significance were Suboptimal relationships with suppliers ($\chi^2 = 5.220$; p = 0.156) and Lack of initial investment ($\chi^2 = 4.790$; p = 0.188). A more detailed analysis showed that micro-enterprises reported more frequent problems with investment and state support. Medium-sized enterprises more often emphasized barriers related to skilled labor and relationships with suppliers. Large enterprises encountered fewer organizational shortcomings and supplier relationship issues. However, these differences cannot be considered statistically significant. Overall, the results suggest that the barriers to green manufacturing are relatively similar across all enterprise size groups.

Result 5: Comparison of Slovakia within the Eco-Innovation Scoreboard (Eco-IS) in the EU

To better understand the context of green manufacturing implementation in Slovakia, it is useful to compare the country's performance in eco-innovation with other EU Member States. This is done using the Eco-Innovation Scoreboard (Eco-IS), which assesses EU countries based on 16 indicators divided into five areas [27]:
• **Inputs into eco-innovation** – investments in environmental research, human and financial resources;
• **Eco-innovation activities** – the extent to which enterprises are active in the field of environmental innovation;
• **Eco-innovation outputs** – number of patents, innovative solutions, and technological applications;
• **Resource efficiency** – resource productivity, energy consumption, CO_2 emissions;
• **Socio-economic results** – impact of eco-innovation on employment and economic growth.

According to the latest data for 2024, Slovakia achieved a score of 98.9 in the Eco-Innovation Index, which is below the EU average (100). This ranks Slovakia among countries with lower levels of eco-innovation performance. By comparison, countries such as Finland, Denmark, and Austria scored above 140, placing them among the leaders in eco-innovation. Slovakia still lags significantly behind Germany and Sweden, where investment in research and innovation in green manufacturing is high [28].

Key factors influencing Slovakia's low score:
• **Insufficient investment in eco-innovation** – Slovakia is among the countries with low levels of public and private investment in environmental solutions [29].
• **Weak cooperation between the public and private sectors** – low levels of research in the field of eco-innovation and insufficient links between academia and industry slowdown the transfer of innovation into practice [29].
• **Limited support from the state** – Slovakia has less effective regulatory mechanisms and support policies in the field of eco-innovation compared to other EU countries [30].

Figure 3 shows the Eco-Innovation Index for 2024, where Slovakia's position in comparison with other EU countries is visible.

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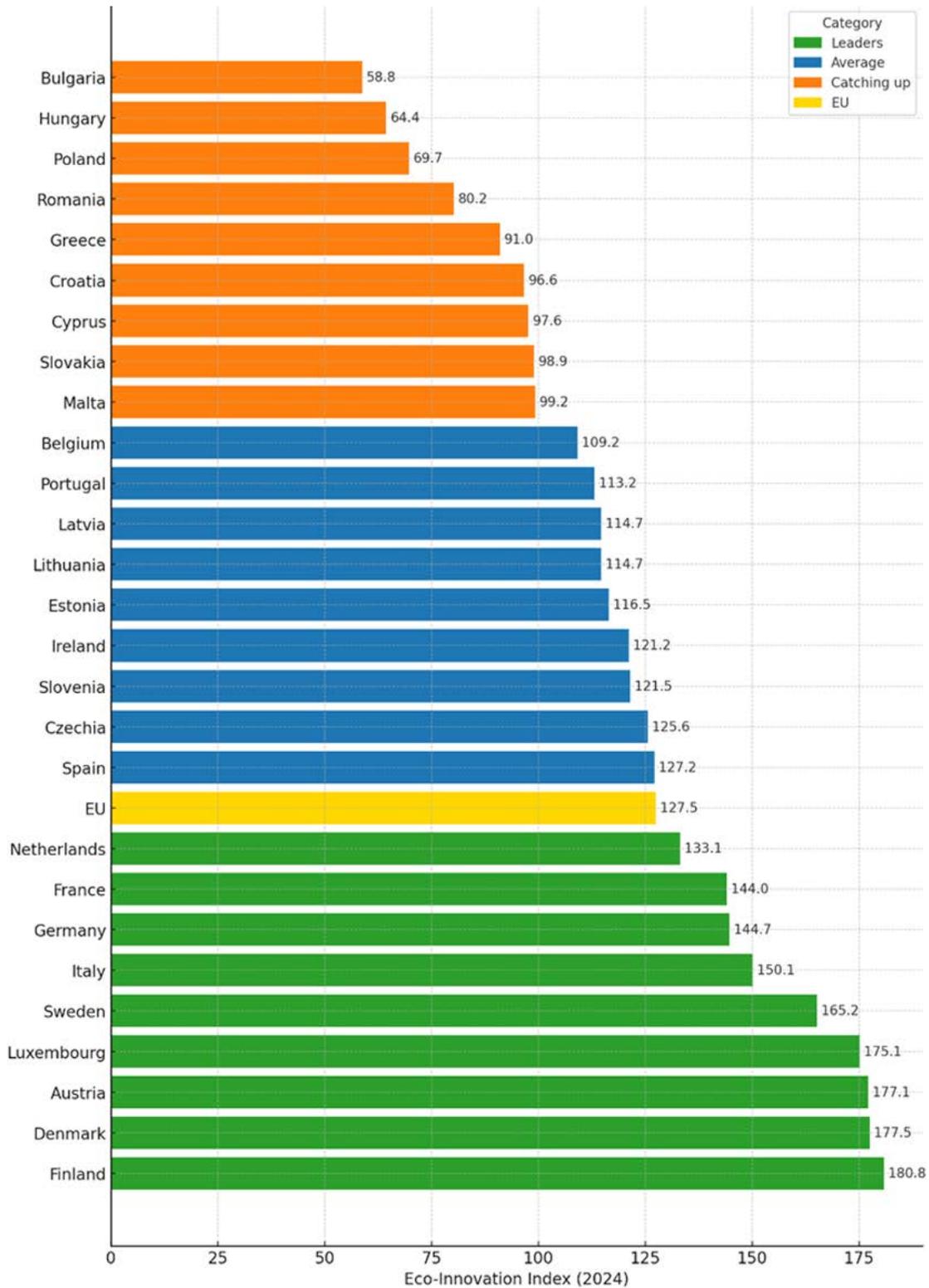
Figure 3 Eco-Innovation Index 2024: Country comparison EÚ [30]

This analysis provides a broader view of the problem of implementing green manufacturing in Slovak industrial enterprises and suggests that overcoming the identified barriers requires increased investment in eco-innovation, technological progress, and stronger support for research and development in environmental areas.

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4   Conclusions

Research conducted in industrial enterprises in Slovakia identified the main obstacles to the implementation of green manufacturing, which include a lack of finance, a shortage of skilled workers, and ineffective supply chains. Regional analysis did not reveal any statistically significant differences between the regions of Slovakia. This finding contrasts with some studies that have reported different approaches to the implementation of green or sustainable manufacturing and specific barriers conditioned by the regional and infrastructural environment. Regional differences in the application of eco-innovations can be significant. For example, a study on regional technological capacities in Europe points out that areas with a historically strong technology sector have a higher rate of green transformation, with Germany among the leaders in this area [31]. Similar findings were reported in a study on regional differences in technological diversification in green transformation, which points to that economically strong regions are better positioned for green diversification, while weaker regions have significantly limited opportunities for transformation [32]. The absence of statistically significant regional differences in our research may be because Slovakia has less economic diversity in industry than, for example, Germany. By comparing our results with the work of Grillitsch & Hansen [33], it is possible to identify different approaches to the issue of green manufacturing and regional inequalities. The authors emphasize that the development of green industries depends on the type of region, with metropolitan regions having greater capacity for innovation and implementation of green technologies [33]. Differences compared to studies in other countries or parts of the world may be due to the small size of the country, lower economic diversity, and relatively low questionnaire response rates.

In the case of Slovakia, it appears that problems such as insufficient funding, weak links between research and practice, and the unavailability of qualified personnel are nationwide in nature. In terms of enterprise size, no statistically significant differences in barriers were confirmed. Based on the number of responses, small and medium-sized enterprises are most influenced by financial constraints, while large enterprises are more likely to encounter a shortage of skilled staff and technological support. These findings correspond with the findings of foreign studies. For example, Rizos et al. [34] and Alayón et al. [35] confirm that small enterprises in Europe often face limitations in accessing financing and information on environmental technologies, which also corresponds to the situation in Slovakia. Similar results were identified in [9] and [15], which showed that the size of an enterprise determines its ability to integrate the principles of sustainable development into its enterprise activities. According to these studies, the most significant barriers to the introduction of sustainability in small and medium-sized enterprises are financial, human, and institutional barriers. This study provides a systematic overview of the barriers to green manufacturing in Slovak industry based on statistical analysis, thereby complementing existing knowledge. The differences identified between the size categories of enterprises show that policies and support mechanisms need to be adapted to the specific needs of enterprises. For small and medium-sized enterprises, improving access to finance is key, while large enterprises need more effective training programs and technological support.

A limitation of this study is the relatively small sample size (88 enterprises), which may affect the representativeness of the results. Future research should focus on sectoral differences, long term trends, and the effectiveness of national policies in ecological transformation. Expanding the sample and taking regulatory and technological changes into account could contribute to a more accurate understanding of the obstacles and solutions in the field of green manufacturing. Nevertheless, it provides valuable insight into the issue of implementing green manufacturing approaches and environmental measures in industrial enterprises in Slovakia and allows the main barriers faced by enterprises to be identified. Although the research sample consisted of only 88 respondents, it can be concluded that even such data provide relevant insights into trends and challenges related to green manufacturing and barriers to its implementation.

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Developing statistical models to analyze traffic accidents and estimate their economic costs in Jordan
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Developing statistical models to analyze traffic accidents and estimate their economic costs in Jordan

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Abstract: This study investigates the behavioral and situational determinants that disrupt the efficient flow of road traffic in Jordan, framing the issue within the broader discipline of transport logistics and flow management. Official crash data obtained from the Public Security Directorate and cost records from local insurance companies were utilized to develop twelve multiple linear regression models that quantify the relationship between human factors and interruptions in traffic, informational, and financial flows. Six models examined the frequency and severity of accidents, while another six analyzed their associated economic impacts. The modeling results identified a consistent set of influential predictors most notably failure to take necessary driving precautions (X8), violation of traffic priorities (X9), and lane misuse (X4) that significantly contribute to both accident occurrence and the resulting financial losses. Most models achieved R^2 values exceeding 0.95, indicating a strong relationship between behavioral inefficiencies and breakdowns in overall road logistics performance. The findings emphasize that driver behavior represents a primary bottleneck in the mobility and cost flow system, directly influencing logistical efficiency across the transport sector. The study highlights the necessity of integrating traffic safety with logistics management by developing preventive strategies, improving regulatory enforcement, and enhancing driver awareness programs. Future research is encouraged to include environmental, temporal, and infrastructural variables to establish a more comprehensive logistics-based framework for understanding and mitigating crash dynamics in Jordan.

1 Introduction

Traffic accidents represent one of the most critical challenges to public safety and sustainable development worldwide particularly in developing countries experiencing rapid increases in vehicle ownership and unplanned urban expansion. From a logistics and mobility-flow perspective, road accidents disrupt the smooth flow of people, goods, and services, leading to severe inefficiencies in transport networks. Among the key determinants, driver behavior remains the dominant factor influencing accident frequency and severity, directly contributing to high accident rates and consequent losses in human life, material resources, and logistical performance [1]. The Hashemite Kingdom of Jordan is one of the countries that is suffering from an increasing burden of traffic accidents, as these accidents directly affect lives, property and infrastructure, as well as their long-term economic and social repercussions.

In light of this reality, there is an urgent need for a careful and integrated study of the problem of traffic accidents, in terms of their size, causes and costs, in order to reach scientific and practical solutions that limit their effects [2]. From this point of view, this research comes to shed light on the traffic reality in Jordan, through a comprehensive analysis of the recorded traffic accident data, which was collected from the competent authorities and includes the total number of accidents, the number of deaths resulting from them, and the number of injuries classified as severe, medium, and simple. The data also included an accurate classification of the causes.

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In this study, SPSS was employed to conduct advanced quantitative analyses, aimed at understanding the relationships between the different variables affecting incidents. The linear regression method was used to build mathematical models that explain the behavior of the data, where six different models were developed based on the independent variables associated with the causes of the accidents, and the best model was chosen from them based on the highest value of the coefficient of determination (R^2), which reflects the strength of the model in interpreting the variation in the data [3,4]. These models were not limited to predicting the number of accidents, but the analysis extended to calculating the economic costs associated with these accidents, which include the costs of deaths, injuries of all kinds, and material damage. Six additional models have been built to represent the cost of traffic accidents, using the same methodology, in order to arrive at a comprehensive visualization that can be used by decision makers to estimate the expected economic losses as a result of accidents, to guide preventive policies and to invest in improving traffic infrastructure and safety.

The significance of this research lies in its dual contribution: it not only describes the existing traffic situation and analyzes the behavioral causes of accidents, but also establishes quantitative, data-driven models capable of predicting accident occurrences and their economic costs. From a logistics and transportation management standpoint, these models enhance the understanding of how disruptions in traffic flows affect the overall efficiency of mobility systems and resource allocation. Moreover, the study provides a scientific framework that integrates statistical analysis with mathematical modeling, supporting decision-makers in optimizing traffic-flow management, improving road-safety logistics, and formulating evidence-based transport policies.

The findings of this research represent a scientific reference that can be built upon in future studies, and are a key pillar for the development of national strategies aimed at improving the reality of traffic safety in Jordan, and reducing the human and material losses incurred by the state and society as a result of this worsening phenomenon.

2 Literature review

Traffic accidents are a contemporary societal issue. According to the World Health Organization (WHO), in 2023, traffic accidents claimed approximately 1.35 million lives and injured between 20 to 50 million people [5]. The majority of injuries sustained in head-on crashes are sustained by the drivers of the cars involved while sliding and rolling over of vehicles are the primary causes of passenger deaths [6].

Accidents are typically categorized into three distinct types: ''fatal'', ''severe'', and ''slight''. Fatal crashes, defined as accidents resulting in the death of one or more individuals, have a profound global impact. The research underscores this, noting that on average, 1.35 million people perish annually in traffic accidents [7]. A fatal accident is the most severe kind of accident and results in at least one death. Some deadly accidents result in the victim's immediate passing, while others cause the victim's death during the next thirty days. This definition, road crash death within 30 days of the crash, is followed by 80 of the 178 countries. A fatal accident may produce legal complexities for the motorists involved in collisions and the penalty will depend on the level of negligence on the part of the other driver. On the other hand, a non-fatal accident causes injuries only and does not result in either an immediate or an eventual death. Moving further a major accident is one that not only causes physical injuries but also considerable damage to vehicles involved in the crash as well as damage to road infrastructure such as barriers, traffic signals, street light poles, etc. [8-10].

Road accident data is classified based on severity. The most severe or Serious accidents refer to incidents that culminate in substantial injuries, non-fatal which may result in such accidents which include fractures, concussions, crushing, severe cuts and lacerations, severe general shock, and other injuries that require emergency medical treatment. The severity of these accidents is typically assessed based on the number of individuals injured and the extent of direct property damage incurred resulting in deaths and serious injuries while minor accidents are characterized by less severe injuries or only vehicle/property damage. Also, a minor road accident is the least severe of all road accidents and causes only minor bruises or sprains. An injured person is hospitalized for less than 12 hours [11-13].

Roadway conditions, encompassing aspects such as traffic congestion and the state of the pavement, play a pivotal role in the incidence of accidents. Research has elucidated an inverse correlation between traffic congestion and the frequency of accidents, while the condition of the road surface is also found to significantly influence the occurrence of accidents [14-16].

Numerous studies have investigated the relationship between environmental, infrastructural, and behavioral factors in shaping the frequency and severity of road accidents. Table 1 summarizes the most relevant research, highlighting the variety of analytical approaches, datasets, and findings across different regions. This synthesis clarifies the methodological trends and gaps that justify the integrated approach adopted in the present study.

As shown in Table 1, most previous studies have focused on behavioral, environmental, and infrastructural determinants of road accidents, with limited attention given to the economic consequences or the integration of cost–frequency relationships. Building upon these findings, the present study employs officially verified datasets from Jordan to develop statistically validated regression models that link accident characteristics with their associated economic costs. This approach aims to provide a practical and evidence-based framework to support decision-making processes, improve road safety policies, and reduce both human and financial losses within the national transport system.

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Table 1 Summary of selected previous studies on factors influencing traffic accidents

No.	Focus / Data Type	Method / Model Used	Key Findings	Research Gap / Limitation
[17-19]	Meteorological, roadway, and driver factors	Correlation and regression analysis	Weather, pavement condition, and human factors jointly affect accident frequency and severity	Most studies isolate variables; few integrate environmental and behavioral dimensions
[20,21]	Road condition & driving behavior	Bayesian classifier, ML	Bayesian models effectively predict risky driver behavior and pavement hazards	Focused on algorithm accuracy, not economic impact
[22,23]	Road design, economic indicators	Linear & logistic regression	Regression effectively links design improvements to lower accident rates	Limited contextual validation in developing countries
[24,25]	Police and behavioral data	Statistical modeling / policy review	Weak enforcement significantly increases accident frequency	Did not model cost or injury severity quantitatively
[26,27]	Driver characteristics & socio-economic context	Comparative analysis	Driver behavior and socio-economic traits drive accident risk	Few localized or Jordan-specific empirical models

Note: Reference numbers correspond to the studies listed in the References section [17-27].

3 Methodology

To achieve the research goals, the available data were collected from the General Security Department through the Jordan Traffic Institute (JTI) for the years 2016 to 2023, which include a huge amount of data such as the total number of accidents, fatalities, injuries, and their causes. The study focuses on analyzing, estimate, and identifying the causes that most affect the occurrence of accidents, and then conclude mathematical models using the linear regression method gained from SPSS statistical program, which is a well-known program with its many capabilities in the field of statistical analysis by adopting the highest value (R^2) among the proposed mathematical models.

As pointed out the causes of traffic accidents is essential for developing countermeasures that can effectively reduce accident rates, assuming these measures are properly implemented. The study also examined the economic consequences of traffic accidents in Jordan, encompassing both human and property-related losses. It estimated the cost of a single fatality and a single injury, then calculated property damage costs, leading to the determination of the overall financial burden.

The objective was to identify the most influential factors contributing to traffic accidents and their associated costs from a range of possible causes. To achieve this, the linear regression coefficient was employed, as it effectively highlights the key variables impacting the total number of accidents. In a simple linear regression model, this coefficient is used to assess the extent to which each independent variable influences the dependent variable by quantifying both the strength and direction of their relationship. This relationship is typically expressed with the multilinear regression equation, as shown in equation (1).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \tag{1}$$

Where:
Y is the dependent variable (to be predicted).
X1, X2, ..., Xn are the independent variables (potential influences).
β1, β2, ..., βn are the regression coefficients that determine the effect of each independent variable on Y.

4 Data collection

The requested data were collected from the Jordan Traffic Institute, the Department of traffic statistics and the Jordan Insurance Federation (JOIF). Companies from 2016 to 2023. The data collected could be categorized into two main groups: statistical traffic accident data for traffic safety models and traffic accident cost data for traffic accident cost models. The data needed are the total number of accidents, fatalities, slight injuries, mid injuries, severe injuries, and property damages for each traffic accident caused in each year from 2016 to 2023. SPSS (Statistical Package Computer Program) was used to determine prediction accident models for traffic safety and traffic accident cost. Also, a relationship between traffic safety models and cost models was found. The collected data can be classified into:

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4.1 Traffic accident data

In this study, the first objective is to analyze traffic accidents. Data were collected from the General Security Department through the Jordan Traffic Institute (JTI) for the years 2016 to 2023. It was organized in statistical tables and prepared in order to represent data in an easy and illustrative way. The total traffic accident, total fatalities, total Sever Injuries, total mid injuries, total Slight Injuries and total Property Damages for each year from year 2016 to year 2023 were considered as dependent variables for statistical analysis. Table 2 shows that the most causes of traffic accidents are due to driver behavior which are considered independent variables.

Because the property damages were not recorded officially, therefore the following calculation was used to estimate P.D.:

$$P.D = \text{Total accident} - [\text{Fatalities} + \text{Sever injuries} + \text{Mid injuries} + \text{Slight injuries}]$$

Table 3 shows the dependent variables for statistical analysis, and Tables 4-9 show the required data for each independent variable from year 2016-2023.

Table 2 The most traffic accident causes in Jordan (independent variables)

Variables	Causes	Variables	Causes
X1	Disregarding a traffic light signal	X8	Not taking the necessary precautions while driving
X2	Going against traffic	X9	Priorities false
X3	Using incorrect lane	X10	Turning in prohibited places
X4	Lane Violations	X11	Tail Gating
X5	Loss of control (Fatigue)	X12	Failing to comply with obligatory signs
X6	Incorrect bending and turning	X13	Incorrect Reversing
X7	Speed limit exceeding	X14	Failure to ensure vehicle stability while parking

Table 3 Shows the total number of accidents, fatalities, slight injury, mid injury, sever injury, and property damages over the eight years (2016-2023) (dependent variables)

Year	Total Accidents (Y_1)	Fatalities (Y_2)	Slight Injury (Y_3)	Mid Injury (Y_4)	Sever Injury (Y_5)	Property Damages (Y_6)
2016	144521	750	15594	4368	1841	121968
2017	150226	685	14751	2706	1495	130589
2018	150398	571	11436	3746	1021	133624
2019	161511	643	10159	6062	792	143855
2020	122970	461	7344	4788	558	109819
2021	160600	589	10423	6325	737	142526
2022	169409	562	9552	6739	805	151751
2023	170058	560	9192	6451	826	153029

Table 4 The traffic accidents for each independent variable (2016-2023)

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	Total
2016	1991	1000	2948	39134	1734	4335	573	59435	12551	2107	12378	4361	1147	827	144521
2017	1956	1337	2991	40703	1798	4358	749	62185	13662	2545	12311	4133	749	749	150226
2018	2105	1341	1427	39693	1644	6012	750	62258	14289	2408	12011	4513	1197	750	150398
2019	2425	1934	2752	40538	2261	5846	1131	66372	15337	2098	13405	4836	1445	1131	161511
2020	2081	1601	2081	29757	2081	3434	859	50657	12355	1967	9954	4425	859	859	122970
2021	2558	1958	3045	40471	2087	5286	946	63263	17017	3045	14136	4816	958	1014	160600
2022	2532	1708	2915	40079	1856	7802	1017	68251	17002	3047	15764	5241	1017	1178	169409
2023	2213	1859	1843	39645	1336	7992	1183	70568	17344	2721	16363	4932	1045	1014	170058

Table 5 Total number of fatality accidents (2016-2023)

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	Total
2016	19	16	15	157	19	41	14	259	67	22	60	30	16	15	750
2017	15	12	19	160	15	27	11	247	61	17	57	23	11	10	685
2018	12	10	8	137	10	25	8	213	52	13	46	20	9	8	571
2019	16	15	14	143	15	26	11	226	58	20	52	24	12	11	643
2020	17	15	17	84	17	20	14	134	42	17	36	23	12	13	461
2021	22	20	24	109	20	29	18	158	54	24	48	27	18	18	589
2022	19	19	21	101	19	29	17	160	49	21	47	26	17	17	562
2023	12	11	12	116	10	29	9	203	54	14	49	23	9	9	560

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Table 6 Total number of slight injury accidents (2016-2023)

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	Total
2016	213	164	104	3956	217	468	99	7612	1202	157	905	327	124	46	15594
2017	192	131	295	3969	176	427	74	6218	1343	252	1194	318	89	73	14751
2018	160	103	108	3019	126	458	65	4734	1086	203	893	332	92	57	11436
2019	151	121	67	2548	143	274	71	4379	964	131	843	304	92	71	10159
2020	124	112	124	1774	124	206	52	3025	723	117	595	264	52	52	7344
2021	166	133	198	2620	83	343	56	4159	1105	198	917	313	71	61	10423
2022	144	101	163	2345	105	400	57	3897	917	172	841	296	57	57	9552
2023	122	101	101	2132	73	431	64	3878	930	147	829	265	64	55	9192

Table 7 Total number of mid injury accidents (2016-2023)

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	Total
2016	60	29	50	1224	52	131	17	1879	336	43	358	141	35	13	4368
2017	35	24	53	728	32	83	13	1128	246	46	219	73	13	13	2706
2018	52	33	25	1001	41	149	18	1550	355	59	293	122	30	18	3746
2019	91	73	81	1563	84	197	43	2495	575	79	502	182	54	43	6062
2020	76	65	90	1205	40	181	24	1884	507	91	421	143	29	32	4788
2021	101	179	120	1757	53	241	57	1924	663	166	665	292	64	43	6325
2022	101	71	119	1702	76	294	42	2592	681	125	627	221	43	45	6739
2023	84	70	70	1496	52	311	47	2649	681	107	604	194	47	39	6451

Table 8 Total number of sever injury accidents (2016-2023)

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	Total
2016	24	24	16	384	20	56	8	989	144	16	108	36	12	4	1841
2017	20	13	31	332	18	54	7	663	145	26	130	42	7	7	1495
2018	14	9	17	278	11	43	5	381	107	18	87	33	13	5	1021
2019	12	9	15	219	11	22	6	262	88	12	94	28	8	6	792
2020	10	7	11	154	11	18	4	169	70	10	62	24	4	4	558
2021	12	10	13	184	7	25	7	275	82	14	72	23	9	4	737
2022	12	6	14	199	11	35	5	305	83	20	77	27	5	6	805
2023	13	11	12	186	7	37	6	343	85	13	77	25	6	5	826

Table 9 Total number of property damages (2016-2023)

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	Total
2016	1675	767	2763	33413	1426	3639	435	48696	10802	1869	10947	3827	960	749	121968
2017	1694	1157	2593	35514	1557	3767	644	53929	11867	2204	10711	3677	629	646	130589
2018	1867	1186	1269	35258	1456	5337	654	55380	12689	2115	10692	4006	1053	662	133624
2019	2155	1716	2575	36065	2008	5327	1000	59010	13652	1856	11914	4298	1279	1000	143855
2020	1854	1402	1839	26540	1889	3009	765	45445	11013	1732	8840	3971	762	758	109819
2021	2257	1616	2690	35801	1924	4648	808	56747	15113	2643	12434	4161	796	888	142526
2022	2256	1511	2598	35732	1645	7044	896	61297	15272	2709	14172	4671	895	1053	151751
2023	1982	1666	1648	35715	1194	7184	1057	63495	15594	2440	14804	4425	919	906	153029

4.2   Estimation of traffic accident cost data

The second objective of the study is to analyze the total costs of traffic accidents in Jordan over the period of eight years (2016-2023). In view of the difficulty of collecting cost information from insurance companies throughout Jordan. Therefore, the cost data were collected from Jordan Traffic Department and Compensation Fund Jordan Insurance (CFJI) only. As shown in Table 10, compensation costs are classified according to their type.

Total traffic accident costs, fatality accident costs, slight accident injury costs, mid accident injury costs, and severe accident injury costs were calculated and presented in Table 11 as dependent variables.

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Table 10 The compensation cost in Jordan

COST TYPE	COST (JOD)
One fatality	20,000
One Sever injury	17,000
One mid injury	3,900
One Slight injury	2,900

During the year 2016, there were 585 fatalities and one fatality cost 20,000 JD. Therefore, the estimated cost of accident fatalities (Y2C) for this year is $20,000 \times 585 = 11,700,000$ JD. As shown in Table 9. The same method of estimation was calculated for total accident cost (Y1C), for mid accident cost (Y4C), for slight accident cost (Y3C), sever accident cost (Y5C), and property damages cost (Y6C).

The results of estimation cost show that an average of 6% fatalities, 20% sever injuries, 15% slight injuries, 5% mid injury, and 54% are property damages of yearly total accident cost.

Table 11 The estimated dependent variables of accident cost from year (2016-2023)

Year	Total Accidents Y1C	Fatalities Y2C	Slight Injury Y3C	Mid Injury Y4C	Sever Injury Y5C	Property Damages Y6C
2016	323558182	15000000	45222600	17035200	62186000	184114382
2017	308014679	13700000	42777900	10553400	50490000	190493379
2018	313160446	11420000	33164400	14609400	34476000	219490646
2019	324136097	12860000	29461100	23641800	26724000	231449197
2020	296580633	9220000	21297600	18673200	18802000	228587833
2021	320387077	11780000	30226700	24667500	24854000	228858877
2022	322628005	11240000	27700800	26282100	27166000	230239105
2023	342615909	11200000	26656800	25158900	27863000	251737209

5 Results of SPSS statistical analysis

SPSS software was used in formulating the regression models by using the method of least squares. The method of least squares is a procedure to determine the best fit line to find linear relationships between dependent and independent variables. The least square method (LSM) is probably the most popular technique in statistics. This is due to several factors. First, the most common estimators can be cast within this framework. For example, the mean of a distribution is the value that minimizes the sum of squared deviations of the scores. Second, using squares makes LSM mathematically very tractable because the Pythagorean Theorem indicates that, when the error is independent of an estimated quantity, one can add the squared error and the squared estimated quantity. Third, the mathematical tools and algorithms involved in LSM (derivatives, eigen decomposition, and singular value decomposition) have been well studied for a relatively long time.

To minimize potential overfitting arising from the limited number of observations, independent variables were screened using correlation analysis and stepwise regression in SPSS. Only the most statistically significant predictors were retained for model construction.

In this study, the dependent variables are: total number of accidents, fatalities, injuries, and property damages shown in Table 3 and Table 11. The independent variables are shown in Table 2, with detailed results presented in Tables 4-9. For this purpose, the multilinear regression equation was used to obtain the relationship between the variables.

5.1 Prediction of traffic accident models

For traffic accident prediction regression models, the dependent variables are: total traffic accidents (Y1), total fatalities (Y2), total slight injuries (Y3), total mid injuries (Y4), total sever injuries (Y5), and property damages (Y6). The independent variables are traffic accidents caused by driver behavior as shown in Table 2. Six models were developed as presented in Table 12.

Table 12 The results of prediction the traffic accident model

Model No.	Regression Models	R^2	Adjusted R^2	CV-R^2 (10-fold)	CV-R^2 (LOOCV)
1	Y1 = -13614.061+ 11.358X1 + 2.258X8	0.990	0.986	0.982	0.980
2	Y2 = -22.223 + 11.439X8	0.964	0.957	0.952	0.950
3	Y3 = 1524.932 + 2.215X4 + 0.857X8 – 5.509X5	0.999	0.999	0.997	0.996
4	Y4 = -145.383 + 3.043X9 + 1.768X4 + 0.694X8	0.999	0.999	0.995	0.994
5	Y5 = -318.633+ 66.525X1 + 1.467X4	0.999	0.998	0.996	0.995
6	Y6 = 1930.473 + 2.414X8	0.976	0.972	0.961	0.959

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5.2 Prediction of traffic accident cost models

For traffic accident cost prediction regression models, the dependent variables are: total traffic accident cost (Y_1C), total fatality cost (Y_2C), total slight injury cost (Y_3C), total moderate injury cost (Y_4C), total severe injury cost (Y_5C), and total property damage cost (Y_6C), as shown in Table 11. The independent variables, representing driver-related behavioral causes of accidents, are listed in Table 2. Six regression models were developed and are summarized in Table 13.

The property damage and accident cost data used in these models were obtained from verified official sources, including the Jordan Traffic Department and compensation fund Jordan insurance. These datasets represent actual financial losses recorded for each accident category, eliminating the need for residual-based or indirect estimation. The use of audited data enhances the reliability and real-world validity of the developed cost models.

Table 13 The results of prediction the traffic accident cost model

Model No.	Regression Models	R^2	Adjusted R^2	CV-R^2 (10-fold)	CV-R^2 (LOOCV)
7	$Y_1C = 99765708.01 + 1.194X_8 + 2.304X_{11}$	0.944	0.921	0.927	0.924
8	$Y_2C = -444469.205 + 11.439X_9$	0.964	0.957	0.951	0.948
9	$Y_3C = 4352655.970 + 2.280X_4 + 0.672X_8$	0.997	0.996	0.993	0.991
10	$Y_4C = 886353.948 + 4.370X_9 + 2.032X_4$	0.983	0.976	0.969	0.967
11	$Y_5C = 79700.176 + 0.015X_{14} - 0.020X_3$	0.998	0.997	0.993	0.991
12	$Y_6C = 711686103.18 + 3.629X_9 + 18.895X_2 + 2.160X_6$	0.991	0.985	0.982	0.980

6   Results and discussion

This section presents the findings derived from twelve multiple linear regression models developed to examine the key factors influencing road accidents in Jordan. The models are categorized into two main groups: the first six address the frequency and severity of accidents and injuries, while the remaining six focus on the associated economic losses. Each model was validated not only through conventional statistical indicators (F- and t-tests, R², and Adjusted R²) but also through cross-validation procedures (10-fold and LOOCV) to ensure model reliability and minimize potential overfitting. All models demonstrated strong explanatory power (R² = 0.94 - 0.999) and consistent performance across validation schemes, confirming the robustness of their predictive capability. The discussion that follows is organized thematically to highlight emerging patterns across accident categories, injury levels, cost components, and recurring behavioral predictors.

6.1 Total number of traffic accidents

The analysis of the regression models revealed that the total number of traffic accidents in Jordan is significantly influenced by specific behavioral violations. Among the models tested, the most robust was Model 2, which identified two key predictors: disregarding traffic light signals (X1) and failure to take necessary precautions while driving (X8). With an R² value of 0.990, the model indicates a near-perfect fit, suggesting that these two variables alone account for the vast majority of variation in accident counts.

This finding is consistent with observations from both field data and traffic enforcement reports in Jordan, where signal violations and inattentive driving are frequently cited as leading causes of incidents at major intersections and urban corridors. Notably, X8 representing general driving negligence emerged as a recurrent factor across multiple outcome models, indicating its broad impact on road safety. The strength of its coefficient further supports the claim that even moderate improvements in driver awareness and caution could lead to substantial reductions in accident frequency.

From a policy perspective, this underlines the urgent need for targeted enforcement and awareness campaigns focused on intersection behavior and defensive driving. Moreover, the findings lend quantitative backing to the anecdotal but widely acknowledged link between poor driving discipline and accident rates in the country.

6.2 Injuries and fatalities (slight, moderate, severe, and fatal cases)

The regression outputs for injury-related outcomes slight, moderate, and severe alongside total fatalities, revealed a consistent pattern: human error and traffic violations remain the primary contributors across all severity levels. Specifically, violations such as lane misuse (X4), failure to yield or observe right-of-way priorities (X9), and again, the lack of necessary precautions while driving (X8) repeatedly emerged as statistically significant predictors.

For slight injuries, Model 3 indicated strong positive correlations with lane violations and inattentive driving, while fatigue-related loss of control (X5) also had a notable negative coefficient suggesting that this factor, though impactful, might be underreported or underdiagnosed. Moderate injuries were similarly associated with the same trio of variables (X4, X8, X9), reinforcing the conclusion that improper driving behavior is a systemic issue, not merely isolated to high-impact crashes.

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In terms of severe injuries, the model demonstrated an exceptionally high R² (0.999), driven primarily by two critical behaviors: running red lights (X1) and illegal lane changes (X4). These types of violations often occur in high-speed or complex traffic environments, where their consequences can be especially severe.

Fatalities, both in frequency and in cost (as discussed in the next section), were most closely tied to failure in observing traffic priorities (X9). This points to a deeper cultural or systemic issue possibly gaps in driver training, enforcement inconsistency, or even infrastructure design flaws that obscure clear priority rules.

Together, these findings not only validate the models statistically but also speak to the urgent need for structural interventions, including stricter lane discipline enforcement, better fatigue monitoring, and enhanced public education on right-of-way rules. The recurring presence of X8 across all injury and fatality models further strengthens the case for targeting inattentiveness and general recklessness in future safety campaigns.

6.3 *Economic costs of traffic accidents*

The second half of the regression analysis shifted the focus from the frequency and severity of traffic incidents to their financial implications. Models 7 through 12 examined the costs associated with various accident outcomes, including fatalities, different injury levels, and property damage. While the dependent variables changed from physical counts to monetary values, the explanatory factors remained largely behavioral in nature underscoring the economic toll of risky driving.

A recurring and notable driver of cost escalation was X8 failing to take necessary precautions while driving. This variable appeared in multiple cost models (slight injuries, accident costs, and property damage), maintaining a statistically significant and positive relationship. Similarly, lane violations (X4), failure to yield priority (X9), and tailgating (X11) featured prominently, especially in models tied to injury and damage costs.

Model 12, which estimates the cost of property damage, showed particularly high sensitivity to driving against traffic (X2), incorrect turning (X6), and ignoring priority rules (X9), reflecting the high-impact nature of these behaviors. Meanwhile, the cost of severe injuries (Model 11) was influenced by less common but critical factors, such as failure to ensure vehicle stability while parking (X14) and incorrect lane usage (X3) variables that, although infrequent, carry disproportionately high costs when they lead to crashes.

These results reinforce the idea that improving road safety is not only a public health imperative but also a fiscal one. The data illustrates how preventable driver behaviors translate directly into economic losses, both for individuals and for public institutions. Incorporating these findings into cost-benefit analyses of enforcement, education, and infrastructure investments could enhance the rational allocation of resources in traffic safety planning.

6.4 *Recurrent predictors and systemic behavioral patterns*

Across all twelve models, a small set of explanatory variables emerged repeatedly as statistically significant and strongly correlated with adverse traffic outcomes both in frequency and in financial cost. Chief among these was X8 (Failure to take necessary precautions while driving), which was significant in nearly every category: total accidents, slight and moderate injuries, property damage, and even total cost estimations. This consistency highlights not only the prevalence of inattentive or negligent driving in Jordan but also its outsized impact on the traffic system.

Closely following X8 were X9 (Violation of traffic priorities) and X4 (Lane violations) each appearing in at least four of the models and significantly contributing to both injury severity and accident-related costs. These violations often reflect deeper infrastructural and educational shortcomings. For example, ambiguity in intersection design, poor signage, or inconsistent driver training may contribute to misunderstandings about right-of-way rules. Likewise, lane violations may result from both behavioral indiscipline and inadequate lane markings or enforcement. Another observation of interest is the context-specific nature of some variables. While X1 (disregarding traffic lights) and X11 (tailgating) appear less frequently, they are tied to high-severity outcomes such as fatal crashes or large-scale costs making them critical despite their lower frequency. Similarly, variables like X14 (failure to ensure vehicle stability when parking) may seem marginal but highlight overlooked risk factors in traffic safety frameworks.

Taken together, these patterns suggest that road safety in Jordan is not a function of isolated risk behaviors but rather a syndrome of recurring violations, many of which are preventable through targeted interventions. The data supports a multi-pronged approach: combining behavioral enforcement (e.g., stricter penalties for lane misuse), infrastructural redesign (e.g., clearer signaling at complex intersections), and public awareness campaigns tailored around high-impact violations. Importantly, the high R² values across all models indicate that such interventions can be data-driven and outcome-oriented, offering a pathway toward measurable safety improvements.

7 Conclusion and recommendation

This study aimed to identify and quantify the most influential behavioral and situational factors contributing to traffic accidents in Jordan, using twelve multiple linear regression models based on official national datasets. The analysis drew on accident statistics from the Public Security Directorate and economic cost data from Jordanian insurance companies, allowing for a comprehensive investigation into both the human and financial dimensions of road safety.

The findings revealed a consistent set of predictors most notably failure to take necessary precautions (X8), violation of traffic priorities (X9), and lane violations (X4) that were strongly associated with both accident frequency and severity, as well as with the corresponding cost burdens. These patterns suggest that traffic incidents in Jordan are not isolated or random but are largely driven by recurring and preventable behaviors. The high explanatory power of the models (with R^2 values exceeding 0.95 in most cases) supports the reliability of these results and provides a solid empirical basis for designing targeted interventions.

By highlighting these critical risk factors, the study contributes actionable insights into the mechanisms behind traffic accidents and offers a data-informed foundation for shaping future safety policies, driver education initiatives, and enforcement strategies. The next section presents a series of recommendations and avenues for future research, aimed at reducing the frequency, severity, and cost of traffic incidents across the country.

The study findings highlight the urgent need to strengthen enforcement of traffic priority and lane-use regulations, particularly given the recurring impact of violations such as failure to yield (X9), lane misuse (X4), and inattentive driving (X8). National awareness campaigns on defensive driving, along with improved driver training and periodic recertification, are essential to address behavioral risk factors. Infrastructure upgrades especially at intersections can reduce confusion and mitigate violations. Insurance companies may also leverage these findings to develop risk-based incentive systems. Future research should expand beyond behavioral factors to include environmental, vehicular, and temporal variables, offering a more comprehensive understanding of crash causation in the Jordanian context.

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