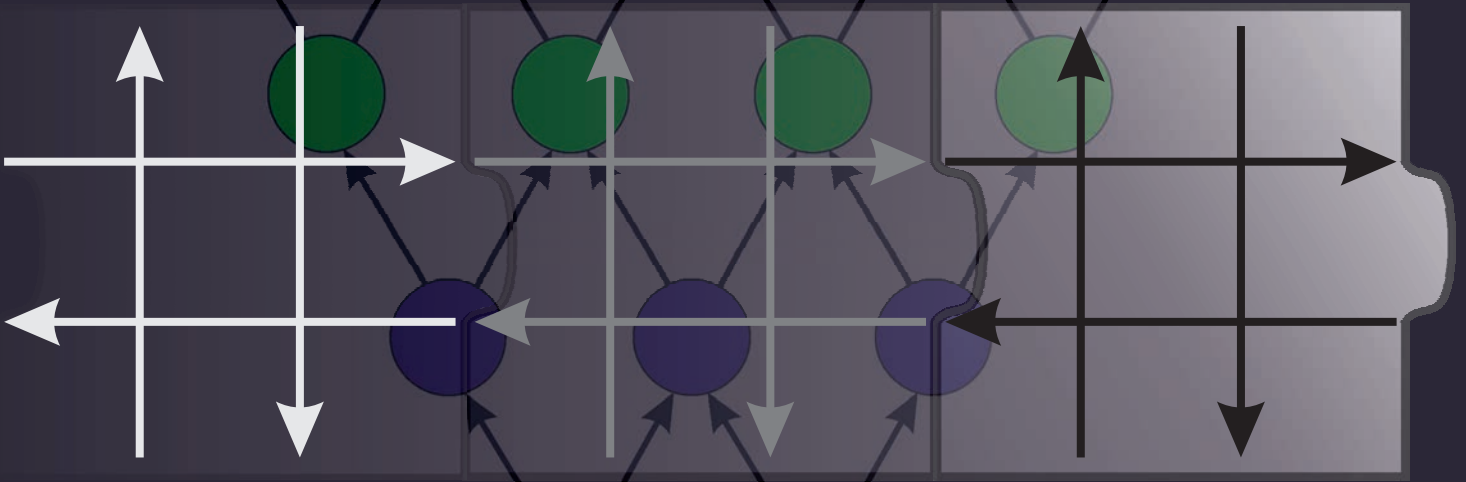


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Model calculation of the impact of IFRS 16 on financial indicators of companies in transport

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Keywords: leasing, IFRS 16, reporting, transport.

Abstract: The study examines the impacts of applying the IFRS 16 standard on operating expenses (OPEX) and other key financial indicators within the Czech transport company environment. The PRISMA 2020 method and visualization using VOSviewer software were used for the literature search. The empirical part is based on data from a major transport company, with over 600 thousand records analyzed, of which 4,105 relevant leasing contracts remained after validation. Five accounting scenarios were compared based on the developed model. The results show that applying IFRS 16 leads to a 4.2% reduction in OPEX, an increase in EBITDA and an increase in long-term assets and liabilities. The study provides evidence of significant accounting and economic differences between the national standard and the IFRS solution and underlines the need to take them into account in management financial decision-making.

1 Introduction

The area of accounting reporting for leasing contracts has undergone fundamental changes in recent years, which significantly affect the presentation of companies' financial positions. These changes are primarily based on the implementation of the international accounting standard IFRS 16 – Leases, which entered into force in 2019. The standard brings a significant adjustment in the approach to lease reporting, especially from the perspective of lessees, who are now obliged to recognize most leasing contracts as part of assets and liabilities on the balance sheet. This has a significant impact on key financial indicators that are commonly used to assess the performance and financial stability of companies.

The changes affect not only the multinational environment. Similar trends are also evident within the framework of national accounting regulations, where there is gradual harmonization with international rules. In this context, it is becoming increasingly important to analyze and quantify the impacts of these changes on specific types of business entities.

This article focuses on a model assessment of the impacts of applying IFRS 16 on selected financial indicators of companies that use leasing to finance heavy trucks. The analysis is based on an extensive dataset provided by a specialized leasing company, which ensures a high degree of relevance and applicability of the results to the real market environment. The aim of this study is to create a model that demonstrates how applying IFRS 16 would be reflected in financial statements and subsequently affect key financial indicators for investors, creditors or company management.

2 Literature review

European countries' national legislation does not have a uniform approach to reporting leasing. For example, the legislation of the Czech Republic (primarily Act 563/1991 Coll., on accounting and Decree 500/2002 Coll. – hereinafter referred to as the Czech legislation or CZ Leg.) regulates leasing in a way that reflects legal ownership - i.e. the lessor reports the owned leased asset on its balance sheet and depreciates it. [1] The lessee reports the asset only off-balance sheet and accounts for the leasing payments as expenses, continuously for the duration of the contract. In terms of the type of contracts, this is done in practice in the same way for all three forms of leasing: financial, operational and reverse, the purpose of which is to improve liquidity for companies while maintaining use of the asset [2].

Fundamental changes in the accounting reporting of leases were introduced by the international standard IFRS 16, valid since 2019. This standard also unified the approach to financial and operating leases for the lessee (except for short-

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term or insignificant leases), however unlike the previous regulation in the Czech Republic, the lessee must report the right of use of the asset and the corresponding lease liability on its balance sheet. The right of use is subsequently depreciated, while the liability is gradually reduced by the paid instalments. For the lessor, the rules remain similar - in the case of a financial lease, the lessor reports a long-term receivable and interest income, in the case of an operating lease, the asset remains on its balance sheet and is depreciated as standard.

Due to the different accounting treatment of leasing under IFRS 16 compared to individual national regulations, it is important to examine how these differences will affect the reported financial indicators of companies. This difference is particularly significant for companies that use leasing extensively to finance assets with high acquisition values, such as heavy trucks. The application of IFRS 16 can have a significant impact on the balance sheet and income statement, thereby affecting key indicators of indebtedness, profitability or liquidity. A model analysis of these impacts is therefore necessary for a correct assessment of companies' financial positions and their comparability across different accounting systems.

To determine whether this research gap was covered, studies containing the terms leasing, IFRS, financial indicators were analyzed from the scientific databases Web of Science and Scopus. After removing duplicate and irrelevant records, 23 articles were available. Below is the distribution over time with the local relevance of individual titles.

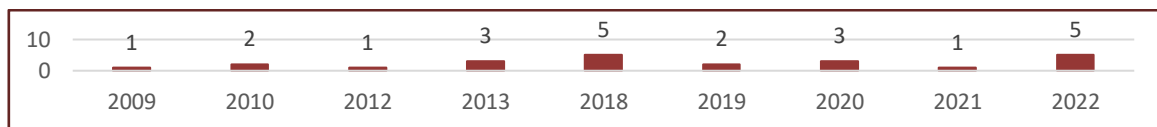


Figure 1 Layout of identified articles in years
Source: own research (2024)

The increase in publications in 2018 was due to the application of IFRS 16 – Leases standard beginning in 2019. Subsequently, the number of publications decreased. In 2022, there was a further increase.

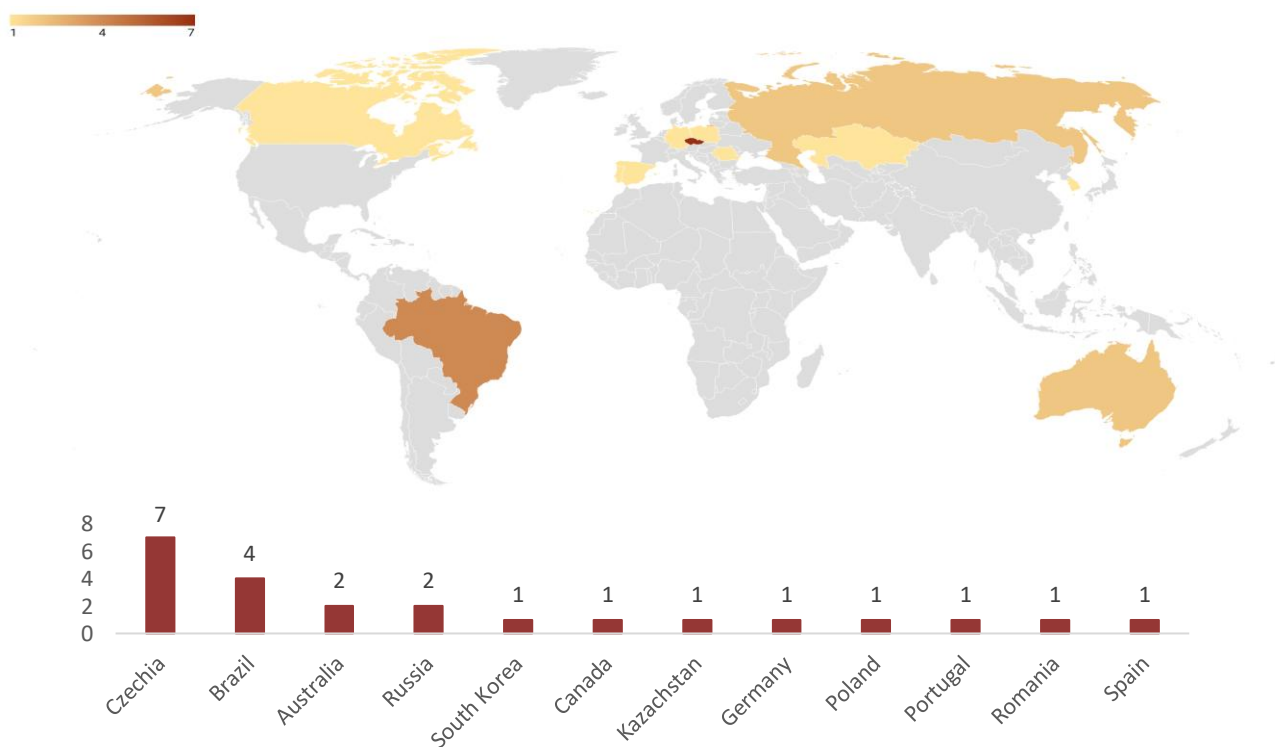


Figure 2 Map and number of published identified articles
Source: own research (2024)

The largest number of records was identified in the Czech Republic, which may have been due primarily to the need to address this different concept. Figure 2 shows the conceptual coherence of the analyzed studies.

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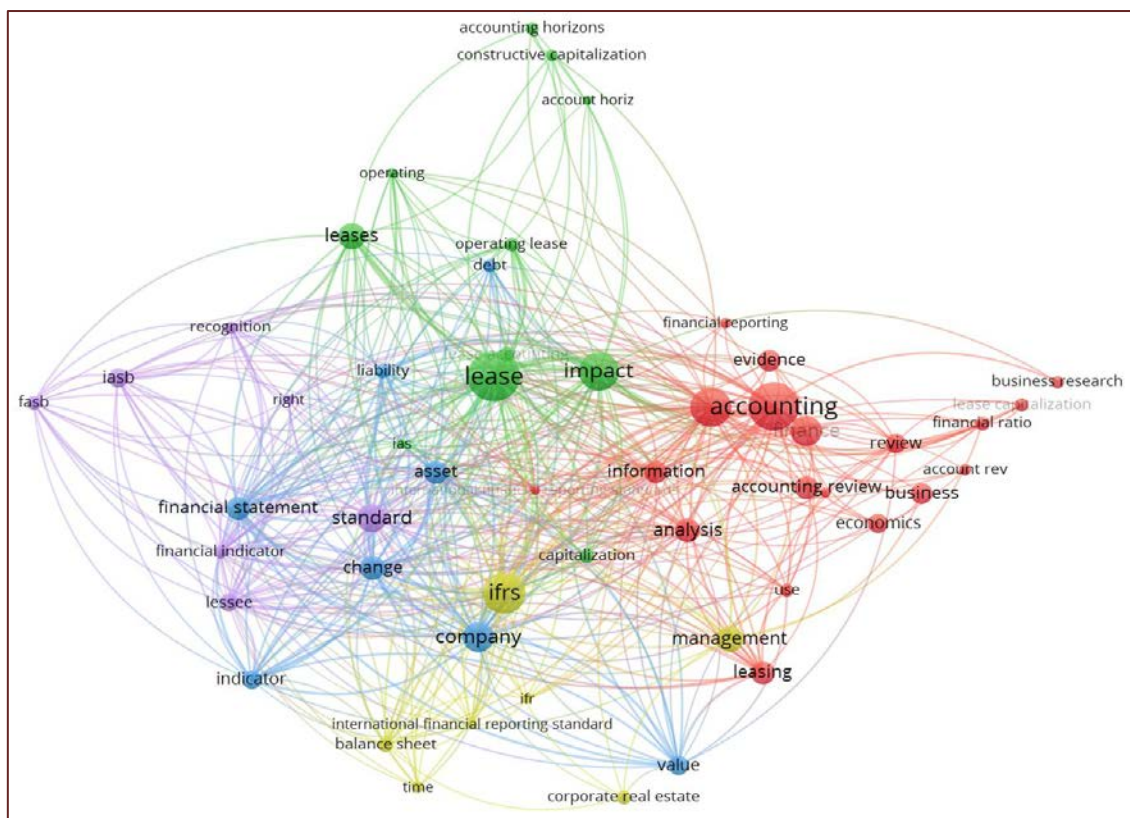


Figure 3 Visualization of identified articles after selection
Source: own research using VOSviewer (2024)

The main terms are categorized by color – lease and related terms are marked in green, in the red field the main term accounting is grouped with other words such as economics, evidence, financial reporting. In the purple part the word standard is colored with IASB, FASB or financial indicators. Similarly, in blue the word company is surrounded by other terms such as liabilities, assets, value or debt. This display confirms the selection of the correct studies to verify the research gap.

Heywood [3] examined the impact of IFRS 16 on the Australian real estate market by comparing statements from 2016 and 2019, finding an increase in tenant assets of \$128–397, leading to an increase in total assets of 2.5–7.7%. Similarly, Levanti [4] analyzed the financial statements of the 15 largest Romanian credit institutions and the impact of IFRS 16 on net assets. Sedláček [5] examined the expected increase in assets and liabilities of Czech industrial companies and pointed out the need for a new interpretation of financial indicators. Svoboda [6] theoretically compared IAS 17 and IFRS 16 and predicted the main differences.

Choi [7] analyzed companies in South Korea and found that large companies deliberately reduced profits to mitigate the negative impacts on profitability and debt ratios even before the transition to IFRS 16. Similarly, Zuniga [8] examined the approach of Chilean companies and confirmed not only the effort to influence results by releasing accumulated profits, but also an increase in share capital to improve debt ratios.

In Brazil, more extensive quantitative modelling has been conducted. De Batista [9] and Colares [10] showed with a set of companies that the application of IFRS 16 led to an increase in the balance sheet total, a decrease in revenues and changes in profitability indicators. Lima [11] followed up with a similar study in Portugal, Sokolova [12] in Russia, with both works documenting the impacts on the balance sheet, income statement and financial indicators. These conclusions were also confirmed by da Silva [13] and Rodrigues [14], who noted that the previous standard did not express economic reality correctly, thus refuting the opinion of the German author Fülbiér [15], who, after his empirical research on the perception of operating leases in German companies, claimed that the change was not necessary. Giner and Pardo [16] analyzed Spanish companies and found that investors reflect operating leases as liabilities, similar to bank loans.

In Kazakhstan, the impacts of the standard were modelled qualitatively [17]. In Europe, Bohušová [18] focused on retail chains and found that the application of IFRS 16 led to an increase in assets by 37%, liabilities by 55% and a slight decrease in equity. Durocher [19] analyzed the opinion of Canadian bankers, who welcomed the capitalization of leases for a better assessment of creditworthiness. Dmitrieva [20] compared leasing and credit for the purchase of real estate and preferred credit financing.

Svoboda [21] modelled the impacts of the IASB and FASB harmonization and showed that IFRS 16 changes the time distribution of costs, which affects the profitability of assets. Luty [22] tested the reliability of data using Benford's law and found that the introduction of IFRS 16 did not disrupt it for leasing companies. Dlasková [23] compared IFRS and Czech regulatory reports for construction companies and demonstrated that the accounting framework used significantly affects the Z-score results. Gláserová [24] summarized the differences between the Czech and international leasing regulations, emphasizing the lower capitalization in the Czech Republic. Beranová [25] focused on the EVA indicator and stated that different accounting systems make its international comparison difficult.

The analysis of the above studies confirmed the need for current, empirical, quantitative research in the Czech environment and at the same time demonstrated the possibility of comparison with international sources, as several studies already exist abroad. At the same time, it can be concluded from the above that the model using the principles of IFRS 16 will lead to a reduction in operating costs (OPEX), thus to an increase in operating profit, and further to an increase in financial costs, so it can be assumed that the total cost reduction will be around 18%, as presented in the study by Dlaskova and Cipovova [23].

3 Methodology

The PRISMA 2020 method was used for the analysis of scientific outputs during the research work. The VOSviewer program was used for visualization, which works on the relational principle between the number of occurrences of a certain expression, subsequently the found links between individual words are also depicted and relational groups marked with different colors are created.

As part of the research, data were obtained from Scania Czech Republic, s.r.o. (hereinafter referred to as the distributor) and from the leasing company Scania Finance Czech Republic, s.r.o. (hereinafter referred to as the leasing company). A total of three source documents were obtained. The first consisted of invoices issued by the distributor company. The second and third sources were obtained from the leasing company. One file contained a list of all leasing contracts. The second file contained information on instalment schedules and payments made. First, sources from the distributor company were processed, which provided information on all issued invoices for the period from 2014 to September 2023. There were 46,214 records in total. The data obtained from the distributor company were processed for the purpose of conducting the research. Duplicate records were removed as were records where the complete necessary information of the distributor was missing were removed. A total of 5,550 records from the distributor company were identified and obtained for the research.

As a second source, we were able to obtain a list of all leasing contracts from the leasing company from 2014 to July 2023. There were 11,497 records in total. Thanks to the identification of relevant vehicles and obtaining their VIN (first step = processing the distributor company's resources), both sources were linked using MS Excel functions. The resulting number of identified contracts was 4,760 records. In this source, it was also possible to obtain the system identification number for the identified contracts.

The third source obtained as part of the research was a list of lease payments made from the leasing company. The detailed information for each payment also included the contract identification number. Thanks to this element, both sources could be linked using MS Excel functions and only relevant data could be obtained for this part of the research. The original number of records in the lease payment file was 427,318 records. After linking, a total of 169,701 records were identified for further processing in the research.

The final step in processing the input data was to eliminate leasing contracts that had error values or durations longer than 72 months. The final analyzed number that was included in the research was 4,105 records.

Data on the cost of loans presented in Table No. 1 were obtained from the ARAD system managed by the Czech National Bank (ČNB) in the loans section under the indicator "Total costs of loans to non-financial corporations in the Czech Republic expressed by the cost of borrowing indicator in percentages".

Table 1 Loan costs in the Czech Republic (in %)

Year	Cost of borrowing	Source date
2014	2,33 %	31. 12. 2013
2015	2,23 %	31. 12. 2014
2016	1,91 %	31. 12. 2015
2017	1,97 %	31. 12. 2016
2018	2,38 %	31. 12. 2017
2019	3,43 %	31. 12. 2018
2020	3,72 %	31. 12. 2019
2021	2,16 %	31. 12. 2020
2022	4,77 %	31. 12. 2021

Source: ARAD [26]

The percentages given were used to calculate the cost of the loan in the case of using external capital. Table 2 shows the values of the cost of equity.

Table 2 Cost of equity used in years

Year	Field	No. of companies	Cost of Equity (%)	Source
2014	Transportation	44	8,92	Report 1/14
2014	Trucking	21	9,44	Report 1/14
2014 Total	Total	65	9,09	
2015	Transportation	42	9,71	Report 1/15
2015	Trucking	20	8,67	Report 1/15
2015 Total	Total	62	9,37	
2016	Transportation	38	10,45	Report 1/16
2016	Trucking	26	8,41	Report 1/16
2016 Total	Total	64	9,62	
2017	Transportation	39	9,65	Report 1/17
2017	Trucking	23	8,26	Report 1/17
2017 Total	Total	62	9,13	
2018	Transportation	38	9,71	Report 1/18
2018	Trucking	28	7,47	Report 1/18
2018 Total	Total	66	8,76	
2019	Transportation	40	9,20	Report 1/19
2019	Trucking	30	9,77	Report 1/19
2019 Total	Total	70	9,44	
2020	Transportation	37	7,66	Report 1/20
2020	Trucking	26	8,59	Report 1/20
2020 Total	Total	63	8,04	
2021	Transportation	36	5,77	Report 1/21
2021	Trucking	27	6,84	Report 1/21
2021 Total	Total	63	6,23	
2022	Transportation	36	6,24	Report 1/22
2022	Trucking	31	7,14	Report 1/22
2022 Total	Total	67	6,66	

Source: DAMODARAN [27]

According to the above methodology, data were obtained for the European market and companies operating in the transportation and trucking categories. For the final use of the percentage of cost of equity (orange lines for each year), the calculation of the weighted arithmetic average of both above-mentioned areas is used. The decisive factor for using of a specific percentage of cost of equity is the year of sale of the truck, or the year of the start of the leasing contract.

Subsequently, the resulting research model was created. It considers individual scenarios. These are:

1) Accounting according to the rules of the Czech Commercial Code in the case of Leasing acquisition

In the Czech Republic, regular monthly leasing payments are directly charged to operating expenses. At the same time, if an advance payment is made at the beginning of the leasing contract, accrual accounting principles are followed. For this reason, the following formula is applied in the first scenario of the resulting model (1):

$$CZ\ Leg. = \sum_{t=1}^n \left(\frac{A}{n} + s_t \right) \quad (1)$$

Where: A advance payment,
 n number of monthly lease payments,
 s_t amount of regular monthly payment at time t ,
 t individual months of the leasing contract.

The total sum of leasing instalments and the advance payment paid is the total value of the leasing contract according to the rules of the Czech Commercial Code.

2) Modelling the calculation according to the Czech Commercial Code in the case of leasing with the application of the cost of equity to the value of the advance payment

The second scenario is based on the first scenario of accounting according to the rules of the Czech Accounting Standards, where the cost of equity will be added to the amount of the advance payment using the future value method. These economic costs are not accounted for, but this factor is decisive for the decision-making of the owners and management of the company when determining the optimal capital structure. In this scenario, the following formula is used (2):

$$CZ\ Leg. + CoE = \sum_{t=1}^n \left(\left(\frac{A}{n} + s_t \right) + \left[\frac{A}{n} * \left(1 + \frac{CoE}{12} \right)^t \right] - \left(\frac{A}{n} \right) \right) \quad (2)$$

The variables are the same as in the first scenario, with an additional variable: CoE - Cost of Equity.

The entire portion of the future aliquot value of the advance payment in each month is reduced by the difference of the monthly value of the advance payment. This value is then added to the original calculation of the monthly cost according to the CZ Leg.

3) Accounting according to the rules of the Czech Commercial Code in the case of purchasing vehicles from own resources

The third scenario models a situation where the acquisition of vehicles would be carried out only from the company's own capital and at the same time there would be actual accounting according to the Czech Accounting Standards. In this case, the acquired asset would be capitalized into the company's assets, which would subsequently be depreciated. The calculation in the resulting model was performed according to the following formula (3):

$$Own\ Capital = \sum_{t=1}^n \frac{(max.60) \cdot PC}{60} \quad (3)$$

Where: PC purchase price of a truck/vehicle,
n number of monthly payments of a theoretical leasing contract,
t individual months of the theoretical leasing contract.

In this scenario, a leasing contract is not considered, as there is a direct purchase from own resources. Monthly costs represent the monthly depreciation value (the model includes leasing contracts with a maximum length of 60 months). The total costs in this scenario are the sum of monthly depreciations over the theoretical leasing contract period.

4) Accounting according to the rules of the Czech Accounting Standards in the case of purchasing vehicles from own resources with the application of the cost of equity

In the fourth scenario, the second and third scenarios are combined. The model will calculate the future value of the invested funds from own resources (as in the third scenario). Its aliquot monthly value will be increased by the cost of equity in the same way as in the second scenario. However, in this scenario, this applies to the total acquisition price. In the resulting research model, the following formula is used (4):

$$Own\ Capital + CoE = \sum_{t=1}^n \frac{(max.60) \cdot PC}{60} * \left[\left(1 + \frac{CoE}{60} \right)^t \right] \quad (4)$$

The variables used in this scenario correspond to the explanations in the scenarios above.

The combination of approaches results in modelling economic costs (not just accounting costs) that reflect monthly depreciation and equity costs due to acquisition from own resources.

5) Accounting according to the rules of IFRS 16

In the case of accounting for leasing contracts according to IFRS 16, leasing contracts are reflected on the lessee's side in the company's non-current assets and are depreciated at the same time. The total lease value is essentially the net present value of future lease payments using the relevant interest rate.

A simplifying condition of the research is the assumption that there are no other circumstances reducing or increasing balance sheet items (final redemption, incentives, etc.). According to the IFRS 16 methodology, the research model is based on the following formula for determining the net present value of a leasing contract (5):

$$NPV\ (IFRS\ 16) = A + \sum_{t=1}^n \frac{s_t}{\left(1 + \frac{i}{12} \right)^{t-1}} \quad (5)$$

The individual variables in the formula used have already been explained in previous scenarios. In addition, the following variable is used here: i – interest rate.

The capitalized net present value of future lease payments is then used to calculate the monthly depreciation that is charged over the term of the lease contract. The following formula is used to calculate it (6):

$$\text{Depreciation (IFRS 16)} = \sum_{t=1}^n \frac{NPV (IFRS 16)_t}{n} \quad (6)$$

Depreciation is charged evenly to the company's operating expenses.

According to IFRS 16, a reduction in the long-term lease liability and financial interest expense are charged monthly. The following formula was used to determine the interest expense in the resulting research model (7):

$$\text{Interest (IFRS 16)} = \sum_{t=1}^n CF_t - NPV (IFRS 16)_t \quad (7)$$

Where: NPV (IFRS 16) NPV of future leasing payments,
CF cash flow of the leasing contract (monthly),
n number of monthly lease payments,
t individual months of the leasing contract.

Interest expense is the difference between the physical funds paid in a given month and the calculated NPV leasing payment for each month.

4 Results and discussion

4.1 Research assumptions

Figures 4 and 5 show descriptive statistics of the final analyzed data sample.

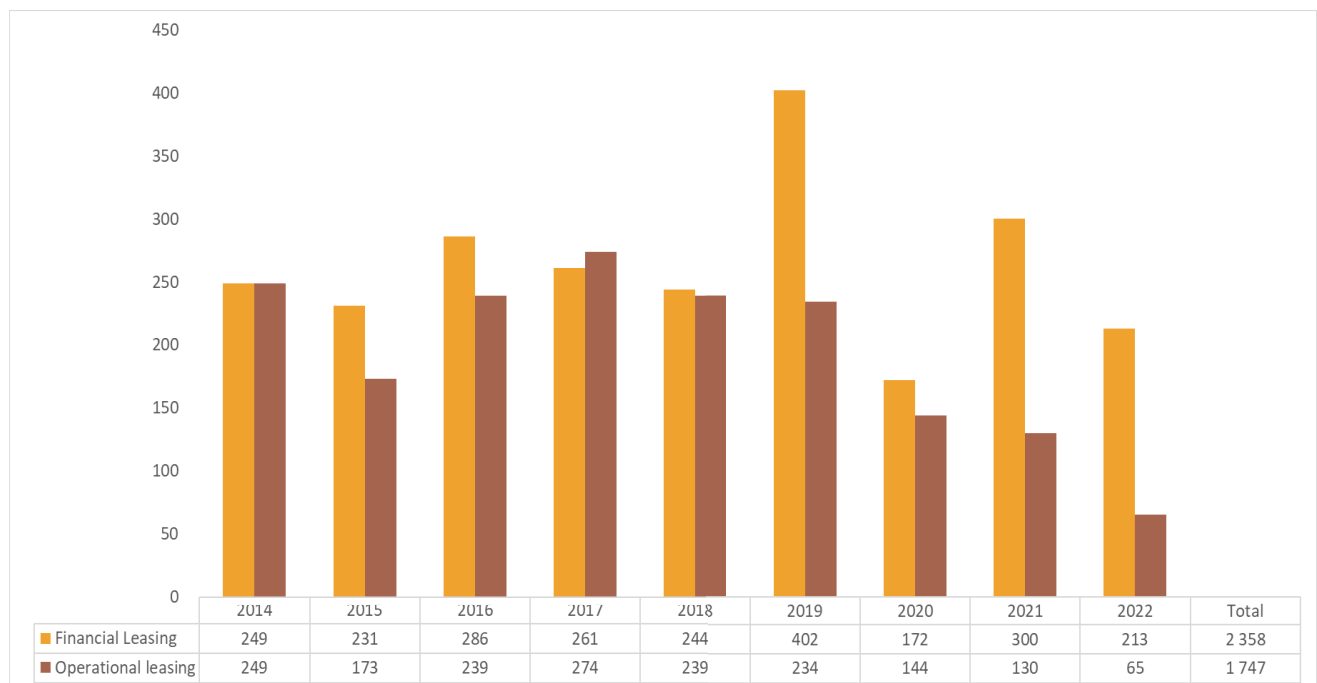


Figure 4 Number of leasing contracts by type in years
Source: own research (2024)

Figure 4 shows that in the period from 2014 to 2022, the year with the highest number of concluded leasing contracts was 2019, when a total of 636 new contracts were concluded. Conversely, a strong drop of -50% can be seen immediately in 2020 due to the already mentioned unfavourable market situation (COVID-19). At the same time, the entire graph also shows the distribution of contracts into individual types of leasing contracts into financial and operational.

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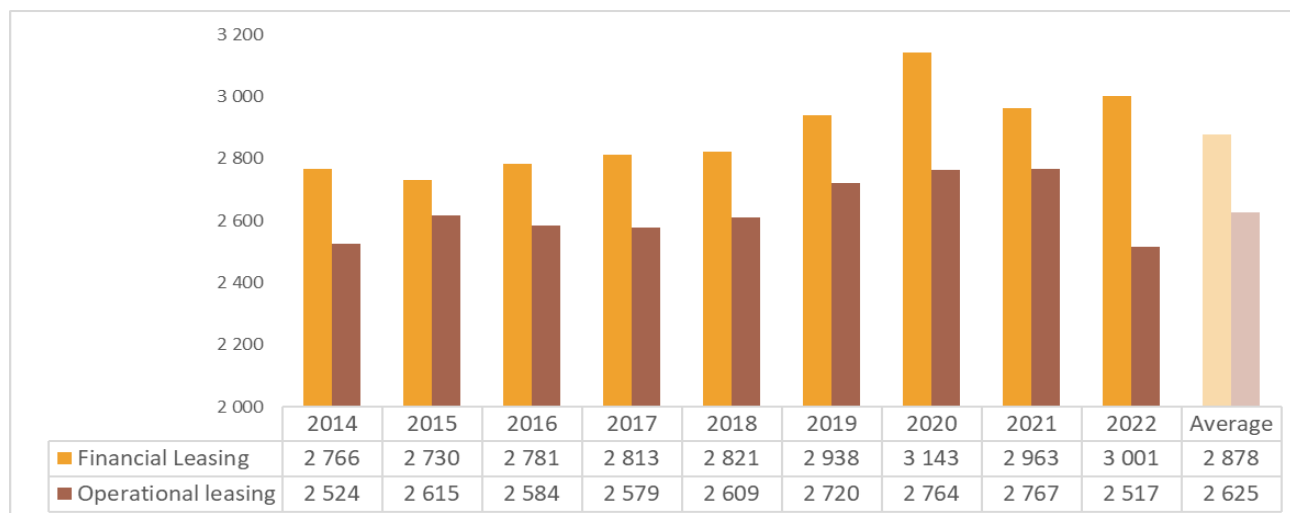


Figure 5 Average selling price of vehicles financed by leasing in years in thousand CZK
Source: own research (2024)

The average selling prices of vehicles financed by the leasing company are shown in Figure 5 in thousands of CZK. Again, there is a division into individual types of leasing (OL/FL). Both types of leasing contracts have experienced different developments in the prices of the underlying assets over the years. In 2015, a decrease in the price of FL vehicles was recorded, but on the other hand, vehicles on OL became more expensive. In combination with the information from Figure 4, possible dependencies or mutually influencing variables can be identified. For example, for OL, an increase of 3.6% in the average selling price of a vehicle was recorded between 2014 and 2015. However, at the same time, there was a decrease in the number of concluded contracts by -31%. In the following years, vehicles financed by OL partially decreased in price or maintained their average price level, until in 2018 they reached approximately the same average selling price as in 2015. In the case of concluded operational leasing contracts, strong increases were recorded in 2016 and 2017.

This example illustrates the fact that there is likely to be a strong correlation between the number of contracts concluded and the average selling price of the underlying asset. However, it is also necessary to consider market developments, market share, etc.

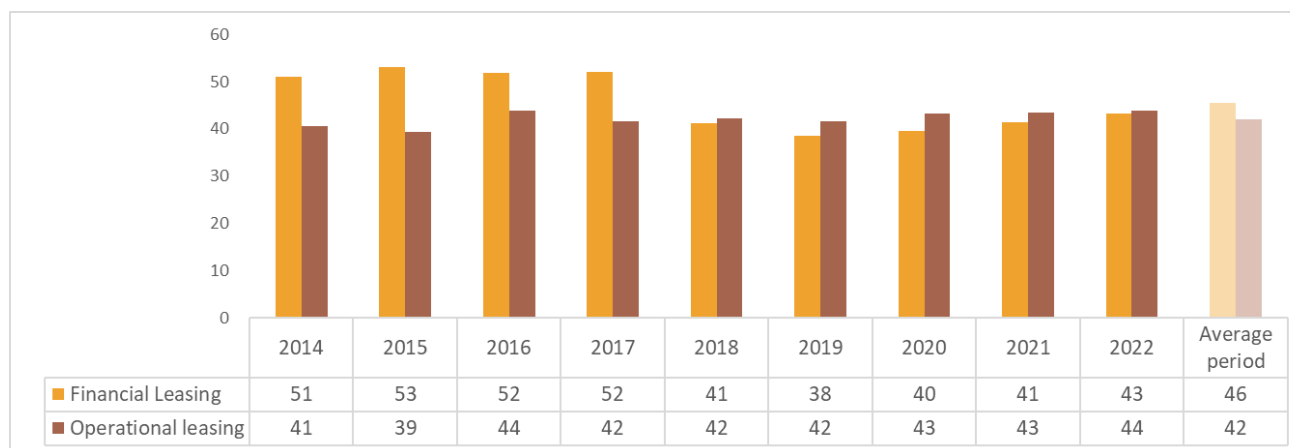


Figure 6 Average length of leasing contract by leasing type and year
Source: own research (2024)

Figure 6 shows a different development in the first years of observation, when the differences between the average number of months of leasing contracts were significantly different between the individual types. In contrast, in recent years the differences between FL and OL have been decreasing, when, on the contrary, the financial leasing product is closed for a smaller number of months than OL in some years.

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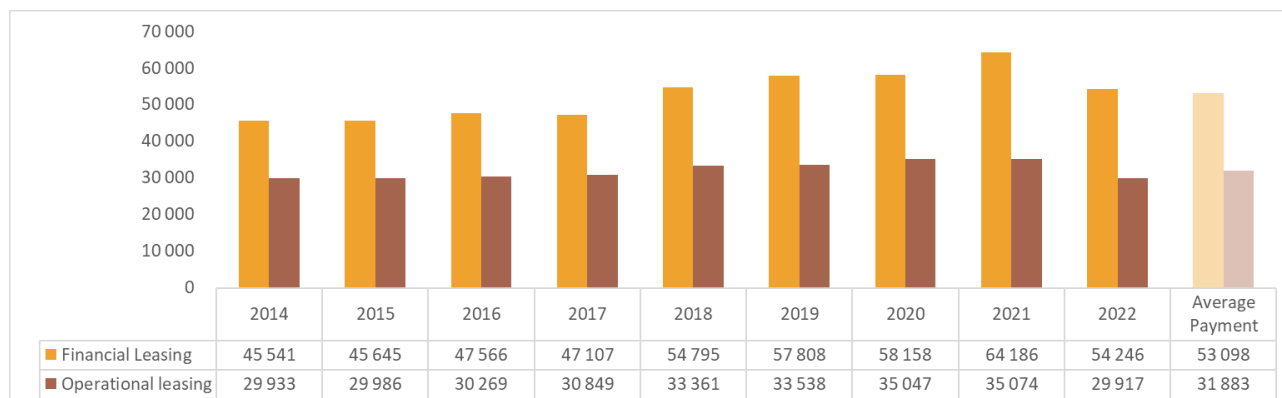


Figure 7 Average monthly leasing payment by leasing type in CZK
Source: own research (2024)

For operating leasing, a relatively stable value can be seen in Figure 7 in the first years of observation. Subsequently, a more significant increase in 2018 and then price increases every year except 2022, where a strong decrease is recorded. For financial leasing, an annual increase is noticeable, in addition to a significant increase in 2018 and a strong decrease in 2022.

4.2 Research model

The results of the research model are presented in the following text using so-called waterfall graphs (all values are given in thousand CZK) and comments. In the first case, the overall research results for leasing contracts without a down payment, i.e. without an increased first instalment, are presented in figure 8:

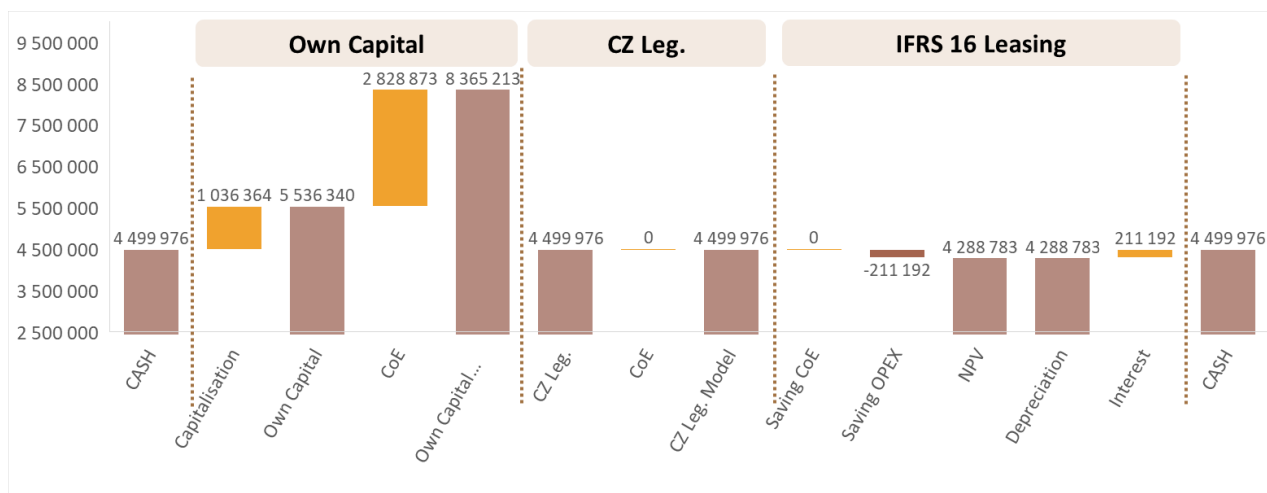


Figure 8 Total effect of research scenarios on sample data without advance payments (waterfalls)
Source: own research (2024)

In the monitored period from 2014 to 2022, the volume of lease payments paid in the identified research sample of cases where the down payment was not paid at the beginning of the contract amounted to 4,499,976 thousand CZK (i.e. almost 4.5 billion CZK). This research sample represents a total of 2,731 observations.

Looking at the middle part of Figure 8 dedicated to Czech Accounting Principles reporting, due to the absence of an advance payment, the value in the Czech Accounting Principles and Czech Accounting Principles Model scenario is the same as the value of the lease payments physically paid. The CoE column in the Czech Accounting Principles Leasing section represents the scenario and costs reflecting the cost of equity, which is not there because there was no advance payment.

In the case of research modelling of a scenario where the volume of vehicles would be purchased from own resources, a significant increase in the depreciation charged to the operating costs of companies is already visible, amounting to 5,536,340 thousand CZK. The difference compared to the physically paid leasing payments in the model is 1,036,364 thousand CZK. The visualization of this effect was presented in Figure No. 8 by the column "capitalization".

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When purchasing vehicles from the company's own resources, the model always calculates monthly depreciation based on the entire purchase price of the vehicle (for the distributor company, it is the selling price). The amount of monthly depreciation is always 1/60 of the purchase price of the vehicle. Subsequently, the number of months of depreciation is always considered only for the duration of the theoretical (source) leasing contract.

Since it is not possible to reflect the expected residual value of the vehicles after the end of their leasing contracts in the model, the entire value of the underlying asset is capitalized in the model, and therefore the regular monthly depreciation reflected in the company's operating costs is increased.

When including the cost of equity in the scenario of purchasing a vehicle from own resources, these economic costs amount to 2,828,873 thousand CZK. Therefore, the scenario reflecting the cost of equity (Own Capital Model) reaches 8,365,213 thousand CZK.

Conversely, the lowest capitalized values in all scenarios in the absence of an advance payment is the scenario of reporting leasing according to the IFRS 16 standard. Its value reached 4,288,783 thousand CZK in the entire set. At the same time, savings in operating costs were identified in the amount 211,192 thousand CZK in financial interest costs. Therefore, the profits of companies (using leasing without an advance payment) at the EBIT level in the monitored period would increase by this value.

The overall results of the research on leasing contracts where an advance payment was made at the beginning are presented in Figure 9. The total analyzed sample of leasing contracts was 1,374.

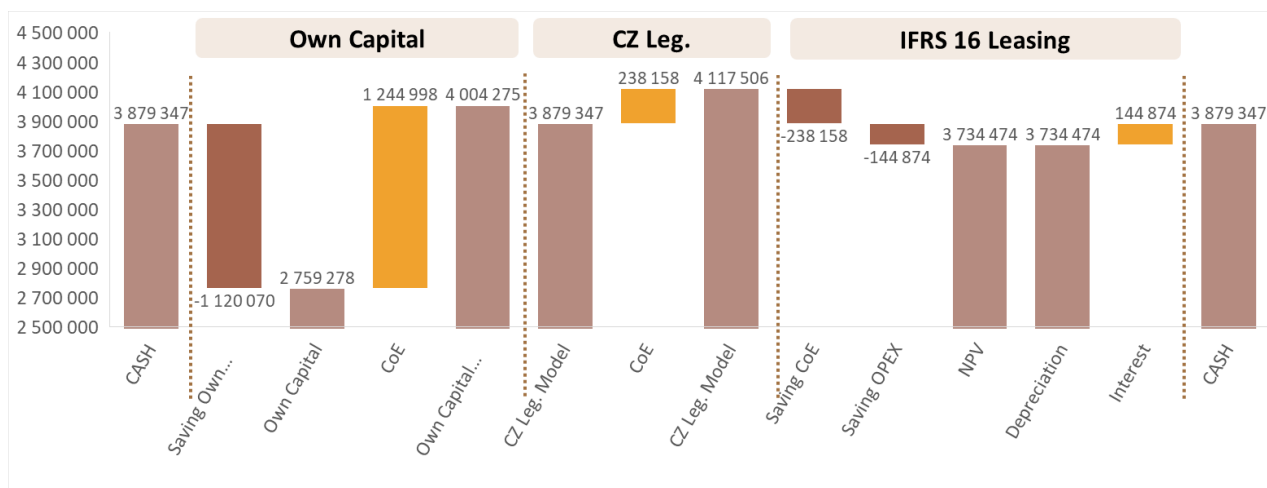


Figure 9 Total effect of research scenarios on sample data with advance payment in CZK (waterfall)

Source: own research (2024)

The total volume of realized financial flows from leasing contracts that included an advance payment was 3,879,347 thousand CZK in the monitored period from 2014 to 2022. The presented data shows a significant difference in the "Own Capital" scenario, when the vehicle is purchased from the company's own resources. The savings, which are quantified here at 1,120,070 thousand CZK, can be considered very significant. The source data were analyzed and checked in this context, and it was found that in these cases the margin for the leasing company increases significantly in contracts that include an advance payment and therefore significantly higher costs for the use of external capital. This significant difference compared to the model where there is no advance payment could be the subject of further scientific research.

However, it would be possible to interpret this difference as a factor where a higher down payment rate is a tool to reduce credit risk for the leasing company for clients whose credit risk would be outside the acceptable limit without such a down payment rate. In such a case, the leasing contract would not be implemented at all. However, after the down payment is paid, the credit risk factors are significantly lower and external financing in the form of leasing is possible. However, the risk premium in the calculation of the leasing payment is significantly higher than in contracts without a down payment. Due to these influences described above, it would be possible to interpret the significantly higher difference between the Cash value and the scenario of purchasing a vehicle from the company's own resources in the research model.

If the cost of equity is included in the "Own Capital" scenario, the value of these economic costs is at the level of 1,244,998 thousand CZK, and the "Own Capital Model" scenario reaches a value of 4,004,275 thousand CZK.

The middle section in the waterfall charts is dedicated to the results of leasing reporting according to the Czech Accounting Standards. The first column in this section expresses the actual accounting recognition of leasing payments according to the Czech Accounting Standards rules. This scenario corresponds to the value of made leasing payments. This is followed by the CoE column expressing the nominal value of the economic costs for the use of equity when paying

the advance payment (238,158 thousand CZK). The last column labeled "CZ Leg. Model" is subsequently the sum of the previous two columns and expresses the value of the physically recorded costs of leasing payments in accounting + an increase by the economic costs for the use of own resources (4,117,506 thousand CZK).

Again, the lowest value of operating costs of a leasing contract is achieved by the reporting scenario according to the rules of the IFRS 16 standard (except for the already mentioned "Own Capital" variant). The saving of operating costs in the amount of financial cost interest in this data set is 144,874 thousand CZK. By this value, companies would achieve a better profit result at the EBIT level.

5 Discussion

One of the biggest differences in the application of IFRS 16 is the change in the financial reporting of leasing contracts on the lessee's side. Operating costs are not fully recognized in the amount of leasing payments, but rather in the form of depreciation of the right of use and financial interest costs. For this reason, there is a significant reduction in total operating costs and a proportional increase in profit at the EBITDA level (as already pointed out by Svoboda [21] or Bohušová [18]). Table 3 below quantifies the differences resulting from the application of IFRS 16. The Czech and IFRS columns are the sum of operating costs (or OPEX) and depreciation. The expressed difference represents the value of financial interest arising from the capitalization of leasing contracts.

Table 3 Values and changes in OPEX + depreciation reported in different adjustments in years (in CZK)

Year	CZ Leg.	IFRS 16	Difference in CZK	Difference in %
2014	98 986 811	94 893 008	4 093 803	4.1
2015	345 683 592	331 555 967	14 127 625	4.1
2016	581 085 515	558 570 441	22 515 073	3.9
2017	777 965 187	748 459 509	29 505 679	3.8
2018	901 245 762	866 870 737	34 375 025	3.8
2019	1 117 803 873	1 073 811 069	43 992 804	3.9
2020	1 092 329 209	1 046 256 839	46 072 370	4.2
2021	1 081 933 129	1 035 348 526	46 584 603	4.3
2022	975 920 352	931 457 175	44 463 177	4.6
2023	658 353 288	626 602 078	31 751 210	4.8
2024	494 266 032	470 917 790	23 348 242	4.7
2025	231 227 018	217 685 238	13 541 781	5.9
2026	22 523 089	20 828 575	1 694 514	7.5
Total	8 379 322 858	8 023 256 951	356 065 907	4.2

Source: own research (2024)

Table 3 presents the results of the research, which is based on the calculation of individual modelled research scenarios (see above). The values are applied to the total data sample, which was identified as the research sample. The distribution of values into individual years in the above table is according to the modelled values based on the initial start date of leasing financing. For this reason, the table also shows future values, as the research sample included leasing contracts that had a contract start date in 2022, but their duration could be calculated into future months based on the research methodology.

The total value divided into individual years corresponds to the sum of the two results presented above in the waterfall charts No. 6 and 7. In the column according to the Czech Commercial Code, it is the sum of the value of leasing contracts without advance payments from chart No. 6 in the amount of 4,499,976 TCZK and from chart No. 7 in the amount of 3,879,347 TCZK. The sum of these two values gives the resulting total sum from table No. 3 in the amount of 8,379,322 TCZK for the Czech Commercial Code accounting scenario. The sum for the IFRS 16 accounting scenario is obtained in the same way.

From the above, it follows that changing the value of the sum of OPEX and depreciation reported financially according to Czech Accounting Standards to the new IFRS 16 standard would cause value change of an average of 4.2%.

The reduction of the company's operating costs in the OPEX classification will occur due to the depreciation of the net present value of future lease payments of the underlying asset, rather than the reporting of the entire value of the lease payments made in the company's operating costs. The IFRS 16 standard therefore considers the time value of money compared to the principles according to the Czech Accounting Standards. In the monitored research sample, this change would mean a reduction of the companies' operating costs (OPEX) by 4.2% totaling approx. 356,066 thousand CZK.

At the same time, the research sample presented:

- growth in EBITDA profit by 8,379,323 thousand CZK,
- growth in EBIT profit by 356,066 thousand CZK (increase by 4.2%),

- decrease in financial result by 356,066 thousand CZK (by 4.2%),
- increase in non-current assets (capitalisation of the right of use) by 8,023,257 thousand CZK,
- increase in long-term liabilities (recognition of lease liability) by 8,023,257 thousand CZK.

The increase in non-current assets by the total value of the net present value of future lease payments will occur due to the capitalization of the leasing contract and thus the recognition of the right of use in the company's assets.

Analogously, the company's liabilities will increase by recognizing a long-term lease liability in the amount of the net present value of future lease payments.

The increase in EBITDA of CZK 8,379,323 thousand is due to the change in the classification of leasing payments from operating expenses (vehicle rental) to depreciation (right of use in assets). For this reason, regular monthly payments will not be charged to the company's expenses, and therefore the EBITDA profit level will be higher by the entire value of the payments made. At the same time, depreciation of the capitalized right of use will be charged to the EBIT profit level, thereby increasing it by the difference between the individual treatments, i.e. by an increase of 4.2%.

Bohušová [18] quantified in her work a positive change in the level of EBIT profit of a median of +2.5%. However, compared to the research sample in this work, she noted the volatility of this percentage in individual companies. The maximum value of the increase in the value of EBIT was 13.29% and the minimum was an increase of 0.09%. In the average annual values for the entire research sample in this presented work, the maximum value is 7.5% and the minimum is an improvement in the level of EBIT of 3.8%.

Another author [16] focused on Spanish listed companies and used regression models to monitor the change in the application of IFRS 16 to financial indicators but did not provide specific values or percentage changes in his study. Similarly, another author [17] analyzed and described the changes by comparing the differences between local adjustments and the new IFRS 16 standard but did not provide specific values or percentage differences in the value of operating costs, assets, liabilities or different levels of profit in her study. Subsequently, other authors mainly reported the percentage effect on the change (increase) in the balance sheet total after the application of IFRS 16 or in their studies only generally described the principles and changes that the new IFRS 16 standard will introduce.

The presented results do not agree with the authors Dlaskova and Cipovova [23], who present a total cost reduction of 18%, therefore the formulated assumption was not fulfilled. The reason may be that the study of these authors focused on assessing the creditworthiness of companies when applying all IFRS together. Therefore, the influence of only IFRS 16 cannot be excluded from these results.

6 Conclusions

The research results show that the transition from Czech Accounting Standards to IFRS 16 has a measurable impact on the cost structure and other key financial indicators of the monitored companies. The most significant impact was the reduction in operating costs (OPEX) by an average of 4.2%, which corresponds to approximately CZK 356 million, and the simultaneous increase in EBITDA by more than CZK 8.3 billion. This resulted in an increase in EBIT by 4.2% and a simultaneous increase in long-term assets and liabilities by more than CZK 8 billion due to the capitalization of leasing contracts. The change in reporting therefore leads to an improvement in profitability at the EBITDA and EBIT levels, but with a negative impact on the financial result due to the increase in interest costs. The results are consistent with some foreign studies but differ from the conclusions of Dlasková and Cipovová [23], which may be due to a different methodology. The research thus provides a specific quantification of the impacts of IFRS 16 in the Czech environment, which has been missing to date.

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An exploratory study of supply chain performance in the digital era: evidence from Morocco

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Keywords: supply chain performance, digital transformation, exploratory study, emerging country, Morocco.

Abstract: This study aims to explore the determinants of supply chain performance in the digital era, with a particular focus on identifying both the benefits and challenges of digital transformation within the Moroccan context. The research seeks to contribute to the understanding of how digital technologies reshape supply chain practices in emerging economies. A qualitative approach was adopted, involving semi-structured interviews with 30 experts and specialists in supply chain management and digital transformation. The collected data were analyzed using a textometric approach, which enabled the identification of recurrent themes, patterns, and relationships among the determinants influencing supply chain performance. The results reveal that digitalization enhances supply chain performance through improved transparency, agility, and cost efficiency, while also fostering stronger collaboration across stakeholders. However, significant challenges persist, including digital infrastructure limitations, high implementation costs, resistance to change, and gaps in digital skills. These findings underscore the dual nature of digital transformation as both an opportunity and a constraint in the Moroccan supply chain landscape. The study provides insights for policymakers and managers to design strategies that leverage digital tools for supply chain optimization while addressing the contextual challenges faced by Moroccan firms. By focusing on Morocco as an emerging economy, this research offers fresh evidence on the role of digital transformation in supply chain performance, contributing to both academic debates and managerial practices in developing contexts.

1 Introduction

At the international level, supply chain performance has emerged as a central concern for firms and policymakers, as it directly affects competitiveness, cost efficiency, and customer satisfaction [1,2]. Global markets are increasingly characterized by heightened competition, complex trade networks, and greater interdependence among firms operating across borders. In this context, the ability of a supply chain to ensure reliability, flexibility, and resilience has become a strategic advantage [3]. Several studies highlight that efficient supply chains contribute not only to operational excellence but also to sustainable growth by optimizing resources, reducing lead times, and enhancing value creation for stakeholders [4]. The international literature emphasizes that supply chain performance is a multidimensional concept, encompassing financial outcomes, service quality, collaboration, and risk management, making it a critical area of research and practice worldwide [5].

With the advent of digital transformation, supply chain performance has gained new dimensions, reshaping the way organizations operate and compete [6,7]. Digital technologies such as big data analytics, artificial intelligence, blockchain, and the Internet of Things have significantly enhanced transparency, visibility, and coordination across supply chain networks. These innovations enable firms to improve forecasting accuracy, reduce lead times, optimize inventory management, and strengthen collaboration among stakeholders [8]. Moreover, digital transformation contributes to cost efficiency and agility, allowing supply chains to respond more effectively to disruptions and volatile market conditions. From a strategic perspective, digitalization not only improves operational outcomes but also creates opportunities for innovation, sustainability, and customer satisfaction, making supply chain performance a central pillar of competitiveness in the digital era [9].

In emerging economies, the digitalization of supply chains presents both opportunities and persistent challenges. While digital tools promise greater efficiency, transparency, and integration, many firms in these contexts face structural barriers that hinder full adoption [10]. Limited digital infrastructure, unreliable internet connectivity, and high investment

costs often restrict the scalability of digital solutions. Moreover, small and medium-sized enterprises (SMEs), which dominate the economic fabric of many developing countries, struggle with financial constraints, insufficient digital literacy, and resistance to organizational change [11]. Institutional weaknesses, such as inadequate regulatory frameworks and fragmented logistics systems, further exacerbate these difficulties. The literature also emphasizes issues of data security, trust among supply chain partners, and the shortage of skilled professionals capable of managing advanced technologies [12]. As a result, while digital transformation is recognized as a driver of competitiveness, its implementation in emerging economies requires tailored strategies that address contextual limitations and resource disparities.

In the Moroccan context, supply chain performance has attracted growing academic interest, evolving alongside the country's strategic orientation toward Digital Morocco 2030. Early contributions, such as [13], focused on identifying the most commonly used performance indicators in Moroccan supply chains, highlighting both existing practices and missing dimensions through Frazelle's model. Building on this foundation, [14] explored reverse supply chain practices, demonstrating that company attitudes and both internal and external barriers critically determine the success of such initiatives, particularly in an environment where research on RSC in developing countries remains scarce. [15] further contributed by analyzing supply chain management practices in the automotive sector, underlining their impact on the financial performance of suppliers, though within a sector-specific scope. More recently, Moroccan research has shifted toward digitalization and sustainability, [16] showed that digital transformation, mediated by supply chain integration, positively affects sustainable performance, while [17] emphasized the importance of proactive risk management to mitigate disruptions and enhance logistic efficiency. Complementing these insights, [18] provided nuanced evidence by disaggregating digital supply chain dimensions, revealing that while information technology and logistics strongly enhance agility and innovation, digital manufacturing may negatively affect performance. Taken together, these works illustrate an evolution from descriptive studies of performance indicators toward more complex analyses linking digital transformation, sustainability, and resilience, while also showing that the impact of digitalization is not uniformly positive but highly context-dependent in Morocco.

Despite these valuable contributions, the literature on supply chain performance in Morocco remains fragmented and reveals several important gaps. First, from a theoretical perspective, there is still a lack of comprehensive models that clearly define the determinants of supply chain performance in the digital era, particularly within the Moroccan context. Second, on the practical level, few studies have examined the concrete implications of digital transformation, especially the dual nature of its benefits and challenges for enhancing supply chain performance. Methodologically, most existing research relies on sector-specific or case-based analyses, while exploratory studies remain rare, even though the Moroccan context is still emerging and rapidly evolving. As noted by [14], few studies have been conducted in developing countries, which further emphasizes the need for context-specific evidence that captures the dynamics of supply chain performance in Morocco under digital transformation.

This study aims to address the limited understanding of supply chain performance in the context of Morocco, particularly under the influence of ongoing digital transformation. While international literature highlights the role of digital technologies in reshaping supply chains, empirical evidence from emerging economies, and Morocco in particular, remains scarce. Thus, this research seeks to explore the determinants of supply chain performance in the digital era, with a particular focus on identifying both the benefits and challenges that digital transformation brings to Moroccan companies. To address these objectives, this study is guided by the following research questions:

Q1. What are the key determinants of supply chain performance in the digital era within the Moroccan context?

Q2. How does digital transformation impact the supply chain performance of Moroccan companies?

Q3. What are the main benefits and challenges of digital transformation in shaping supply chain performance in Morocco?

To address the above research questions, a qualitative approach was adopted, as it provides deeper insights into complex and evolving phenomena such as supply chain performance in the digital era. Data were collected through semi-structured interviews with 30 experts and specialists in supply chain management and digital transformation across various Moroccan industries. This method allowed the capture of diverse perspectives and practical experiences. The collected data were subsequently analyzed using a textometric approach, which facilitated the identification of recurrent themes, patterns, and relationships among the determinants influencing supply chain performance. This methodological choice was particularly suitable for exploring an emerging and under-researched context, enabling both theoretical enrichment and practical insights.

2 Methodology

2.1 Methodological approach

Given that this study addresses a relatively new topic within a context that has rarely been investigated, an exploratory design is considered appropriate. Exploratory studies are particularly suited to contexts where the theoretical foundations are still emerging, and where little prior empirical work exists to guide the research [19,20]. In such cases, a qualitative approach is recommended, as it allows researchers to capture rich, in-depth insights into complex phenomena and to

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generate new theoretical perspectives that can later be tested quantitatively [21]. Accordingly, this study adopts a qualitative exploratory approach to investigate the determinants of supply chain performance in the digital era in Morocco, as well as the benefits and challenges associated with digital transformation [22]. This methodological choice ensures flexibility in data collection and analysis, while enabling a deeper understanding of the perceptions and experiences of experts and practitioners.

2.2 Data collection

Data were collected through semi-structured interviews conducted with 30 experts and specialists in supply chain management and digital transformation operating in different Moroccan industries (Table 1). Semi-structured interviews were chosen because they allow flexibility in exploring the perspectives of participants, while still ensuring consistency in addressing the core research questions.

Table 1 Characteristics of interviewees

Characteristics	Frequency (n)	Percentage (%)
Gender		
Female	12	40%
Male	18	60%
Age		
25–35 years	7	23%
36–45 years	15	50%
46–55 years	8	27%
Educational Qualification		
Master's degree	20	67%
PhD	10	33%
Professional Experience		
5–9 years	8	27%
10–15 years	12	40%
More than 15 years	10	33%
Current Position		
Logistics Director	5	17%
Logistics Manager	12	40%
Logistics Assistant/Agent	13	43%
Sector		
Service sector	15	
Trade sector	8	
Other sectors (Primary sector, Industry, etc.)	7	

Source: Created by the authors

An interview guide structured around three main thematic axes was developed to steer the discussion and ensure comprehensive coverage of the study objectives (Table 2). The selection of participants was based on their expertise, professional background, and active involvement in supply chain activities, ensuring the relevance and richness of the collected data.

Table 2 Main axes of semi-structured interview

Main Axes	Description
Axe 1	Determinants of supply chain performance in the digital era within the Moroccan context.
Axe 2	Impact of digital transformation on the supply chain performance of Moroccan companies.
Axe 3	Main benefits and challenges of digital transformation in shaping supply chain performance in Morocco.

Source: Created by the authors

2.3 Data analysis procedure

After completing the data collection phase, the interview transcripts were analyzed using a textometric approach, which is particularly suitable for exploring large volumes of qualitative data. Textometry enables a systematic examination of textual material by combining both quantitative and qualitative techniques to identify patterns, recurrent themes, and conceptual structures within participants' discourse [23]. This method provides valuable insights into the frequency and co-occurrence of words, thereby uncovering the underlying organization of narratives related to supply chain performance.

For this purpose, the analysis was conducted using IRaMuTeQ (Interface de R pour les Analyses Multidimensionnelles de Textes et de Questionnaires), an open-source software specifically designed for textual data analysis [24,25]. IRaMuTeQ allows several forms of analysis, including word frequency analysis, descending hierarchical classification,

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and correspondence analysis, which facilitate the identification and visualization of emerging themes [26,27]. In this study, the identified themes were grouped into semantic clusters, providing a clearer picture of the determinants, benefits, and challenges of digital transformation in shaping supply chain performance in Morocco. This approach not only ensured analytical rigor but also enabled the extraction of nuanced insights directly grounded in expert perspectives.

3 Results and discussion

3.1 Descriptives statistics

Before proceeding to thematic and interpretative analyses, it is important to present the general descriptive statistics of the corpus (Table 3). These indicators provide an overview of the textual data collected from the semi-structured interviews and offer a first understanding of its richness, diversity, and suitability for textometric analysis.

Table 3 General statistical analysis of the corpus

Indicators	Values
Number of texts	3
Number of text segments	208
Number of occurrences (tokens)	7,507
Number of forms (types)	1,175
Number of lemmas	1,153
Number of hapax	439 (5.85% of occurrences – 38.07% of forms)
Number of active forms	1,140
Number of supplementary forms	13
Active forms with frequency ≥ 3	536
Average occurrences per text	2,502.33
Average forms per segment	36.09
Number of classes (clusters)	5
Classified segments	142 / 208 (68.27%)

Source: Created by the authors

The corpus is composed of three texts segmented into 208 text segments, yielding a total of 7,507 occurrences and 1,175 different forms. This indicates a sufficiently large and diverse dataset to support robust textual analysis. The number of lemmas (1,153) is close to the number of forms, suggesting a limited level of lexical variation, as expected in interviews focusing on a specific professional domain such as supply chain management.

The presence of 439 hapax (words occurring only once) represents 5.85% of total occurrences and 38.07% of forms, reflecting both the richness and the specificity of the vocabulary used by interviewees. This highlights the emergence of key technical terms linked to supply chain performance and digital transformation. Regarding active forms, 1,140 words were effectively mobilized in the analysis, while 536 had a frequency equal to or higher than three, confirming the presence of recurrent themes. The average of 2,502.33 occurrences per text and 36.09 forms per segment demonstrates the density of discourse and the consistency of contributions across participants.

The classification procedure identified five main semantic classes from the data, with 142 segments out of 208 successfully classified (68.27%). This rate of classification is considered satisfactory in textometric research, as it indicates that more than two-thirds of the discourse could be structured into coherent thematic clusters. This provides a solid foundation for the subsequent interpretation of determinants, benefits, and challenges of digital transformation in shaping supply chain performance in Morocco.

To further explore the discourse of experts and specialists, a lexical analysis was conducted on the corpus. Table 4 presents the 50 most frequently used active words, which provide a first indication of the dominant themes and concepts associated with supply chain performance in the digital era within the Moroccan context.

Table 4 The 50 most frequently used active words

Order	Active forms	Freq.	Order	Active forms	Freq.
1	Supply chain	71	26	optimization	19
2	stock	60	27	flexibility	19
3	logistics	58	28	coordination	19
4	companies	54	29	reliability	18
5	time	52	30	IA tools	17
6	costs	46	31	IOT	16
7	Customer satisfaction	40	32	ERP	16
8	market	38	33	Digital transformation	14
9	Inventory management	33	34	profitability	13
10	delivery time	33	35	Procurement management	13

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11	risks	31	36	resilience	12
12	efficiency	31	37	Logistics flows	12
13	disruptions	30	38	transportation	11
14	systems	29	39	Logistics operations	11
15	Logistics performance	29	40	Artificial intelligence	11
16	planning	26	41	agility	11
17	responsiveness	25	42	ability	11
18	Moroccan companies	25	43	warehouse	10
19	challenge	25	44	Service quality	10
20	cost	24	45	competitiveness	10
21	Flow management	23	46	agility	10
22	optimizing	22	47	Operational efficiency	9
23	automation	21	48	logistics_costs	9
24	suppliers	19	49	Competitive advantage	9
25	strategic	19	50	stakeholders	8

Source: Created by the authors

The most frequently occurring terms, such as supply chain (71), stock (60), logistics (58), and companies (54), underline the centrality of operational management and firm-level practices in shaping supply chain performance. High-frequency words like time (52), costs (46), and customer satisfaction (40) confirm that efficiency, cost control, and service quality remain key performance indicators for Moroccan firms.

Several words reflect the emphasis on operational processes, such as inventory management (33), delivery time (33), planning (26), flow management (23), and procurement management (13), showing that performance measurement is strongly linked to resource allocation, responsiveness, and timely deliveries.

The presence of terms such as risks (31), disruptions (30), resilience (12), and reliability (18) highlights the increasing awareness of vulnerabilities in supply chains and the need for proactive risk management, especially in an uncertain business environment.

Digitalization is also reflected in the lexical field with words like IA tools (17), IoT (16), ERP (16), digital transformation (14), and artificial intelligence (11). Although their frequencies are lower compared to traditional logistics terms, their presence indicates a growing integration of digital technologies into Moroccan supply chains.

Finally, strategic dimensions appear through terms such as competitiveness (10), competitive advantage (9), strategic (19), and stakeholders (8), pointing to the importance of aligning supply chain performance with long-term business objectives and external collaborations. Taken together, these findings suggest that Moroccan supply chains are still heavily focused on classical performance drivers (cost, stock, delivery, efficiency), while progressively incorporating digital tools and resilience strategies to address emerging challenges.

To gain deeper insights into the structure of the discourse, a descending hierarchical classification (DHC) was conducted using the Reinert method. This analysis groups text segments according to the co-occurrence of words, thereby revealing distinct lexical worlds related to supply chain performance in the digital era. The dendrogram in Figure 1 illustrates the five main classes that emerged from the corpus (Table 5), each representing a specific thematic dimension of the experts' discourse.

Table 5 Summary of lexical classes (Reinert Method)

Class	Percentage of segments	Thematic title	Main utilized concepts
Class 1	14.3%	Cost reduction and sustainability	Reduction, development, logistics costs, compliance, service quality, environmental, CSR, optimization
Class 2	21.1%	Risks, shortages, and service failures	Poor, delays, shortages, insufficient, failures, customer satisfaction, logistics performance, additional costs
Class 3	20.4%	Challenges of digital transformation of supply chains	Challenge, adopt, digital transformation, supply chains, agility, collaboration, competitiveness, strategies
Class 4	17.6%	Forecasting and adaptive capabilities	Adjust, role, algorithms, anticipate, demand, artificial intelligence, forecasting, procurement, production, efficiency
Class 5	26.1%	Real-Time technologies and traceability	Real time, ERP, IoT, BI, cloud, tracking, monitoring, smart, logistics operations, traceability

Source: Created by the authors

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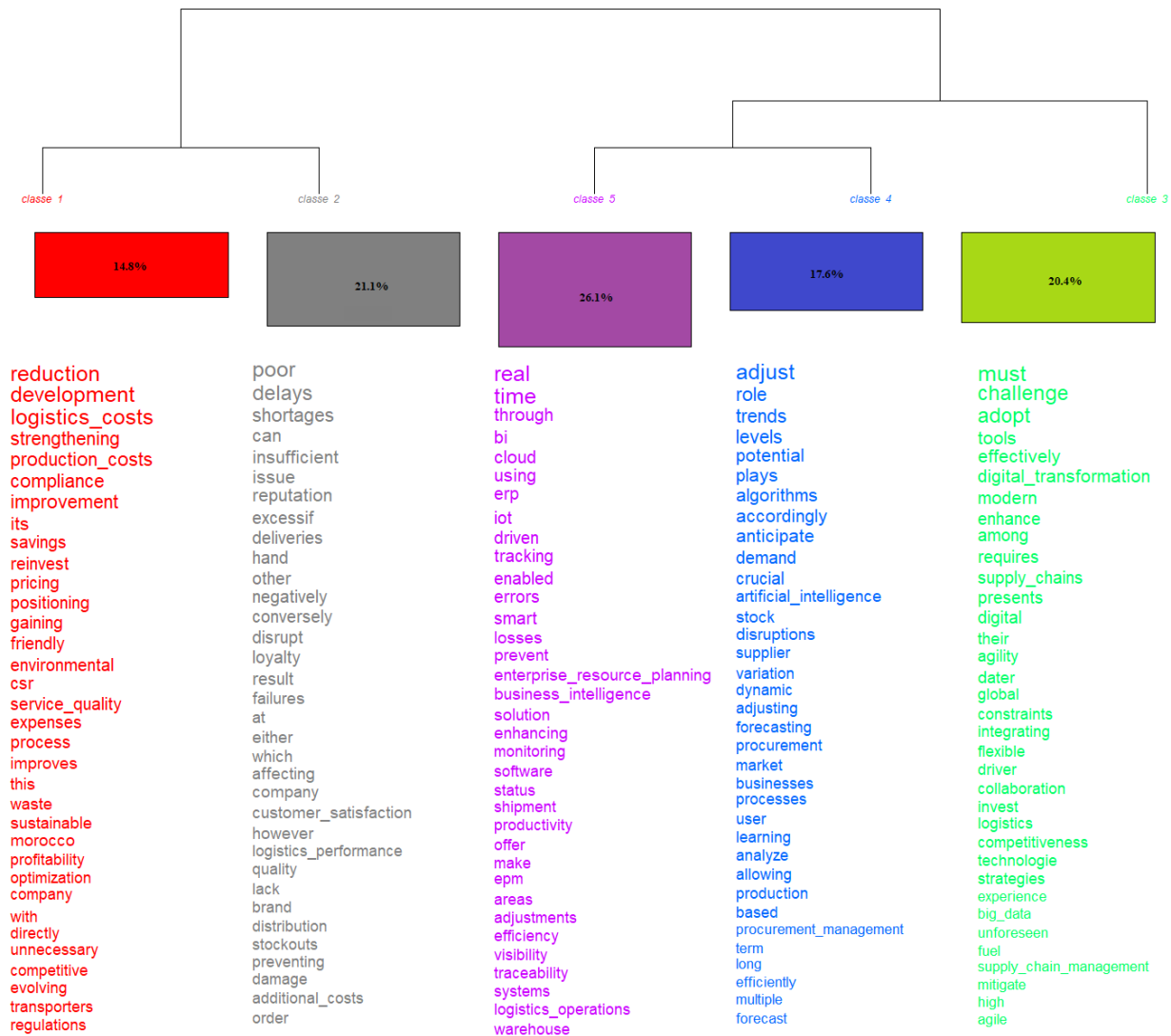


Figure 1 Results of the classification method Reinert

Class 1: Cost Reduction and Sustainability (14.3%)

This class highlights the centrality of cost reduction and sustainable practices in Moroccan supply chains. The frequent appearance of terms such as logistics costs, production costs, compliance, service quality, and CSR shows that firms are highly concerned with balancing efficiency and responsibility. The discourse suggests that reducing costs is not only a financial imperative but also linked to competitiveness and long-term resilience. Furthermore, the references to environmental responsibility and corporate social responsibility (CSR) reflect an increasing awareness among Moroccan companies of the need to integrate sustainable development into their supply chain strategies. This indicates a shift from traditional cost-cutting approaches toward more holistic models that consider both economic and environmental performance.

Class 2: Risks, Shortages, and Service Failures (21.1%)

The second class is dominated by words such as delays, shortages, failures, insufficient, customer satisfaction, and additional costs. It represents the risks and vulnerabilities that disrupt supply chain performance. Experts emphasize the negative consequences of poor coordination, insufficient resources, and distribution failures, which directly impact customer satisfaction and company reputation. The lexical field highlights both external risks (e.g., shortages, transportation disruptions) and internal inefficiencies (e.g., stockouts, excess costs). This class underscores the need for Moroccan companies to develop risk management frameworks and to adopt proactive strategies for mitigating disruptions, particularly in a volatile and uncertain business environment.

Class 3: Challenges of Digital Transformation (20.4%)

This class centers on the opportunities and constraints of digital transformation in Moroccan supply chains. Words such as digital transformation, agility, collaboration, competitiveness, strategies, and adopt indicate that firms recognize the potential of digital tools but also face significant obstacles in implementation. The discourse shows that the adoption

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of new technologies requires substantial investments, cross-company collaboration, and organizational change, which can be particularly challenging for small and medium-sized enterprises. Furthermore, the class reflects the duality of digitalization: while it offers pathways for enhancing competitiveness and agility, it also brings unforeseen challenges such as infrastructure gaps, skills shortages, and cultural resistance.

Class 4: Forecasting and Adaptive Capabilities (17.6%)

This class is associated with predictive and adaptive capacities that are crucial for managing supply chains in the digital era. Terms such as forecasting, anticipate, demand, artificial intelligence, algorithms, procurement, and production suggest a focus on using advanced tools to better predict market variations and adjust operations. The discourse indicates that Moroccan firms are increasingly aware of the role of artificial intelligence and algorithm-based solutions in supporting forecasting and decision-making. Adaptability and learning capacity emerge as key factors in strengthening supply chain resilience. This reflects a strategic shift from reactive problem-solving to proactive anticipation and planning.

Class 5: Real-Time Technologies and Traceability (26.1%)

As the largest class, this cluster emphasizes the importance of real-time technologies in modern supply chains. The frequent use of terms like real time, ERP, IoT, BI, cloud, tracking, monitoring, and traceability highlights the critical role of digital infrastructure in enhancing visibility and responsiveness. These technologies enable firms to monitor logistics flows, improve shipment tracking, and ensure greater operational transparency. The class also points to the emergence of smart systems that integrate data-driven solutions, offering Moroccan companies the ability to reduce errors, increase productivity, and enhance customer trust. However, while these technologies provide significant benefits, their implementation may require overcoming barriers related to costs, digital literacy, and technological readiness.

3.2 Detailed results

To complement the DHC and provide a spatial representation of the relationships between lexical units, a factorial correspondence analysis (FCA) was performed. This method allows the visualization of associations between words and classes by projecting them onto factorial axes. Figure 2 presents the results of the FCA, which highlights the semantic proximity of terms and the underlying structure of discourses around supply chain performance in the digital era. The first two axes explain a significant proportion of the total variance, illustrating how experts' narratives are organized around distinct but interconnected dimensions. This analysis facilitates a more nuanced interpretation of the corpus, by linking thematic classes to their most representative concepts and showing how cost reduction, risk management, digital adoption, adaptability, and real-time technologies coexist and interact in the Moroccan context.

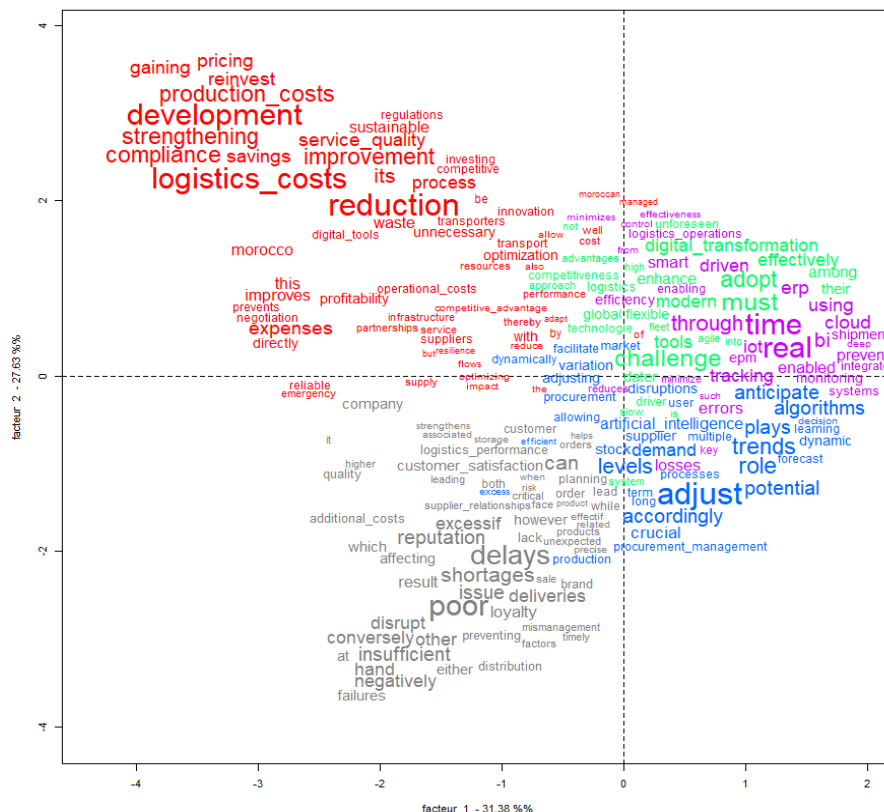


Figure 2 Factorial correspondence analyses (FCA)

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The factorial correspondence analysis (FCA) provides a visual representation of the relationships between the most frequently used terms and the thematic classes previously identified. The first two axes together explain a substantial part of the variance (Factor 1 = 31.38%; Factor 2 = 27.63%), offering a meaningful interpretation of the underlying structure of the corpus.

Upper-left quadrant (Class 1 – Cost Reduction and Sustainability):

This area is dominated by terms such as logistics costs, production costs, reduction, compliance, service quality, and environmental. It illustrates a discourse focused on cost optimization and sustainability, where reducing expenses is strongly linked to improving profitability and integrating socially responsible practices (CSR). This quadrant confirms the importance Moroccan companies attribute to financial efficiency while progressively adopting sustainability principles.

Lower-left quadrant (Class 2 – Risks, Shortages, and Service Failures):

Here, words such as delays, shortages, insufficient, failures, reputation, and customer satisfaction prevail. This reflects the vulnerability of supply chains to disruptions and inefficiencies, highlighting operational risks that negatively impact customer trust and brand reputation. The FCA thus reinforces the idea that risk management remains a structural challenge for Moroccan firms, particularly in contexts of resource shortages or weak coordination.

Upper-right quadrant (Class 3 – Challenges of Digital Transformation):

This quadrant clusters terms such as digital transformation, challenge, adopt, agility, competitiveness, and strategies. It reflects a narrative on the need for Moroccan companies to embrace digital technologies while acknowledging the barriers that hinder successful adoption (costs, skills, and cultural resistance). This positioning suggests that digital transformation is perceived as both an opportunity for competitiveness and a source of significant challenges.

Lower-right quadrant (Classes 4 & 5 – Forecasting, Adaptability, and Real-Time Technologies):

The terms real time, ERP, IoT, tracking, algorithms, forecasting, and anticipate dominate this space. It highlights the role of advanced technologies and predictive capabilities in improving supply chain agility, traceability, and responsiveness. The discourse here emphasizes the strategic use of artificial intelligence, big data, and business intelligence tools to anticipate demand, prevent errors, and enhance real-time decision-making.

The FCA confirms the complementarity of the five classes by showing their spatial organization: Traditional concerns (cost and risk management) dominate the left side, reflecting enduring priorities in Moroccan supply chains. Digital transformation and advanced technologies dominate the right side, representing emerging drivers of competitiveness and resilience. This duality illustrates a transition phase: Moroccan companies remain anchored in cost efficiency and risk minimization while progressively moving toward digital adoption and data-driven supply chain performance.

To complement the classification and FCA, a similarity analysis was carried out to map the co-occurrence relationships among the most frequent terms in the corpus. Figure 3 presents the graphical representation of these associations, where clusters illustrate groups of words that frequently appear together in the experts' discourse. This network structure provides insights into how concepts are interlinked, offering a clearer view of the role digital transformation plays in shaping supply chain performance.

Cluster 1 (Green) – Performance and Competitive Advantage

This cluster groups terms such as performance, supply chain management, logistics operations, business intelligence, and competitive advantage. It highlights the strategic dimension of supply chain performance, showing how companies perceive digital tools as enablers of operational excellence and sources of competitive advantage. The strong association with business intelligence suggests that data-driven decision-making is becoming central for Moroccan companies aiming to strengthen their position in competitive markets.

Cluster 2 (Red) – Flow Management and Digitalization

The second cluster centers on words like supply chain, flow management, digitalization, logistics flows, logistics costs, management systems, and digital platforms. This indicates that digital transformation is closely tied to the optimization of flows and systems, aiming to reduce costs and improve process efficiency. The co-occurrence of digital transformation and Moroccan companies also shows that experts explicitly link modernization efforts to the national context. This cluster reflects the operational backbone of supply chains, where digital platforms play a key role in ensuring smoother flows and greater integration across stakeholders.

Cluster 3 (Blue) – Customer Satisfaction and Operational Efficiency

The third cluster is dominated by terms such as customer satisfaction, inventory management, logistics performance, delivery times, service quality, procurement management, operational efficiency, and artificial intelligence. This cluster clearly connects digital technologies (e.g., AI, automation) with improvements in customer service, delivery performance, and procurement processes. It demonstrates that digitalization is not only about internal efficiency but also about enhancing the external dimension of supply chain performance through better customer experience and reliability.

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The similarity analysis reveals that digital transformation impacts supply chain performance through three interconnected dimensions:

- Strategic impact (Cluster 1) – by fostering competitiveness and strengthening supply chain management with advanced decision-making tools.
- Operational impact (Cluster 2) – by optimizing flows, reducing costs, and leveraging digital platforms for integration and efficiency.
- Customer-oriented impact (Cluster 3) – by improving service quality, delivery times, and overall customer satisfaction through technology adoption.

Overall, the analysis shows that Moroccan companies view digital transformation as both a driver of internal optimization and a pathway toward external value creation. While efficiency and cost reduction remain central, the discourse emphasizes that the ultimate goal of digital adoption is to enhance agility, reliability, and competitiveness in increasingly dynamic markets.



Figure 3 Similarity analysis representation

3.3 Results discussions

3.3.1 Determinants of supply chain performance in the digital era

The findings of this study indicate that supply chain performance in the digital era is shaped by a combination of operational, technological, and strategic determinants. The experts interviewed emphasized both traditional drivers, such as inventory management, cost efficiency, and delivery performance, as well as emerging factors linked to digitalization, such as the integration of advanced technologies, real-time information sharing, and predictive capabilities. These determinants interact to reinforce competitiveness, enhance resilience, and improve customer satisfaction. Table 6 summarizes the main determinants of supply chain performance in the digital era as identified in the Moroccan context.

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Table 6 Determinants of supply chain performance in the digital era

Determinants	Description
Cost Efficiency	Ability to reduce logistics and operational costs through optimization and resource management.
Inventory Management	Effective monitoring and control of stock levels to minimize shortages, delays, and excess costs.
Delivery Performance	Meeting customer expectations in terms of delivery times, reliability, and service quality.
Digital Integration	Adoption of ERP, IoT, and digital platforms to streamline logistics flows and enhance visibility.
Real-Time Information	Use of real-time tracking, monitoring, and data analytics for better decision-making and responsiveness.
Forecasting and Predictive Capabilities	Application of AI, algorithms, and business intelligence to anticipate demand and manage risks.
Collaboration and Coordination	Strengthening inter-organizational relationships with suppliers, customers, and partners through digital connectivity.
Resilience and Risk Management	Ability to anticipate, absorb, and recover from disruptions to ensure supply chain continuity.
Sustainability Orientation	Integration of environmental and CSR practices into supply chain strategies to align with global sustainability standards.
Competitiveness and Innovation	Leveraging digital transformation as a driver for strategic differentiation and long-term competitive advantage.

Source: Created by the authors

3.3.2 Impacts of digital transformation on supply chain performance

The results of this study show that digital transformation has a multidimensional impact on supply chain performance. Beyond traditional efficiency gains, digital technologies contribute to enhancing visibility, agility, and collaboration across the supply chain. At the same time, they enable Moroccan companies to anticipate risks, improve customer satisfaction, and strengthen competitiveness. However, the impact is not uniformly positive, as challenges related to implementation costs, digital readiness, and organizational resistance persist. Table 7 summarizes the main impacts of digital transformation on supply chain performance, as identified in this research.

Table 7 The impacts of digital transformation on supply chain performance

Impacts	Description
Efficiency Improvement	Streamlines processes, reduces operational costs, and minimizes waste through automation and digital platforms.
Enhanced Visibility	Real-time monitoring and tracking enable better control over logistics flows and decision-making accuracy.
Agility and Responsiveness	Digital tools allow supply chains to quickly adapt to demand variations and external disruptions.
Integration and Collaboration	Facilitates coordination between suppliers, customers, and stakeholders through shared digital platforms.
Risk Mitigation	Predictive analytics and AI help anticipate disruptions, shortages, and delays, thereby reducing vulnerabilities.
Customer Satisfaction	Improves service quality, delivery reliability, and personalization, enhancing the overall customer experience.
Competitiveness	Provides firms with new capabilities to innovate, differentiate, and strengthen their market positioning.
Sustainability Support	Digitalization helps reduce carbon footprint, optimize resource use, and align with CSR commitments.

Source: Created by the authors

3.3.3 Benefits and challenges of digital transformation within the Moroccan context

The empirical findings indicate that while digital transformation is widely perceived as a catalyst for improving supply chain performance in Morocco, its adoption is accompanied by significant challenges. On the one hand, digital tools create opportunities for efficiency, agility, and customer orientation, reinforcing firms' competitiveness. On the other hand, structural barriers, resource constraints, and organizational resistance limit the full realization of these benefits, particularly among small and medium-sized enterprises. Table 8 summarizes the key benefits and challenges of digital transformation as identified in the Moroccan context.

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Table 8 The benefits and challenges of digital transformation within the Moroccan context

Benefits	Challenges
Cost Reduction and Efficiency: Automation, ERP, and IoT reduce logistics and operational costs while minimizing errors.	High Implementation Costs: Investments in technology, infrastructure, and training remain prohibitive for many firms.
Enhanced Visibility and Traceability: Real-time monitoring and data analytics improve control over flows and inventories.	Limited Digital Infrastructure: Weak internet connectivity and technological gaps constrain digital adoption, especially outside urban areas.
Agility and Responsiveness: Digital tools allow firms to adapt quickly to demand fluctuations and disruptions.	Skills Shortages: Lack of trained personnel and digital literacy slows down adoption and integration of new technologies.
Improved Customer Satisfaction: Better service quality, delivery reliability, and personalization enhance customer trust.	Resistance to Change: Cultural and organizational inertia make it difficult to embrace digital innovation.
Collaboration and Integration: Shared digital platforms strengthen coordination among supply chain partners.	Cybersecurity Risks: Increased dependence on digital systems exposes firms to data breaches and security threats.
Sustainability Orientation: Digital tools support eco-efficient practices and alignment with CSR objectives.	Regulatory and Institutional Gaps: Lack of clear frameworks and incentives hinders large-scale digital transformation.

Source: Created by the authors

Digital transformation is fundamentally reshaping supply chain performance (SCP) in Morocco through a dual and context-dependent dynamic. First, the findings confirm that traditional operational determinants—such as cost efficiency, inventory management, delivery reliability, and customer satisfaction—remain central in shaping SCP. This aligns with prior research emphasizing that supply chain performance is inherently multidimensional and strongly rooted in operational excellence and cost optimization [1,3]. Even in the digital era, Moroccan firms continue to evaluate performance primarily through logistics costs, stock levels, and delivery times, which confirms earlier Moroccan evidence highlighting the predominance of operational indicators in SCP measurement [13].

However, the study demonstrates that these traditional determinants are increasingly being reconfigured through digital technologies. The strong presence of terms related to ERP, IoT, cloud systems, real-time tracking, and business intelligence indicates that visibility and traceability are emerging as structural pillars of performance. This supports empirical findings suggesting that digital transformation enhances supply chain capabilities by improving transparency, coordination, and data-driven decision-making [6,7]. In line with the triple-A supply chain perspective, digital tools strengthen agility, adaptability, and alignment, which in turn positively influence sustainable and competitive performance [9]. In the Moroccan context, digitalization appears first as an information infrastructure that enhances monitoring and flow optimization before evolving into a broader innovation driver.

Moreover, the results highlight the growing role of predictive and analytical capabilities in strengthening supply chain resilience. The discourse around forecasting, algorithms, artificial intelligence, and demand anticipation reflects a shift from reactive management to proactive and anticipatory supply chain strategies. This finding is consistent with recent studies showing that machine learning and AI-based systems improve agility, risk mitigation, and inventory optimization [3,5]. In emerging economies, such digital capabilities are particularly valuable in addressing volatility and uncertainty, thereby reinforcing supply chain viability and resilience [8]. Nevertheless, the adoption of advanced analytics remains conditional upon data quality, digital maturity, and human competencies.

Importantly, the study reveals the dual nature of digital transformation. On one hand, digitalization enhances efficiency, visibility, collaboration, customer satisfaction, and competitiveness, corroborating prior empirical evidence that links digital transformation to improved supply chain performance and integration [7,9,16]. On the other hand, significant structural barriers persist. High implementation costs limited digital infrastructure, skills shortages, organizational resistance, and cybersecurity risks constrain the full realization of digital benefits. These constraints are consistent with research on supply chain management in emerging economies, which emphasizes financial limitations, institutional weaknesses, and technological gaps as major adoption barriers [10,11,12]. Thus, digital transformation does not produce automatic performance gains; rather, its impact is contingent upon contextual readiness and organizational capabilities.

Compared to previous Moroccan studies, this research extends the literature in several ways. Earlier works focused on performance measurement frameworks [13], reverse supply chain practices [14], or sector-specific impacts of SCM on financial performance [15]. More recent studies examined digital transformation and sustainable supply chain performance [16], risk management and resilience [17], and the differentiated impact of digital supply chain dimensions [18]. Building on these contributions, the present study offers a more integrative and exploratory perspective by identifying a comprehensive set of determinants that combine operational, technological, relational, and sustainability dimensions. It also empirically confirms that digitalization in Morocco operates as a transitional and uneven process, where traditional performance logics coexist with emerging digital imperatives.

In sum, the study contributes scientifically by providing contextualized empirical evidence from an underexplored emerging economy [10], by adopting a rigorous qualitative and textometric methodology grounded in systematic discourse analysis [23-26], and by proposing an integrated framework of SCP determinants adapted to the digital era. The findings demonstrate that supply chain performance in Morocco is at a strategic inflection point: while cost control and operational efficiency remain dominant priorities, digital transformation introduces new capabilities, real-time visibility, predictive analytics, and collaborative platforms that can significantly enhance resilience and competitiveness, provided that infrastructural, human, and institutional barriers are effectively addressed.

4 Conclusions

This study aimed to explore the dynamics of supply chain performance in the digital era, with a particular focus on the Moroccan context. The results provide insights into the determinants, impacts, and dual nature both benefits and challenges of digital transformation. The findings show that supply chain performance is shaped by a set of interconnected determinants. Traditional drivers such as cost efficiency, inventory management, and delivery performance remain crucial. At the same time, new determinants linked to digitalization, such as real-time information sharing, forecasting capabilities, collaboration through digital platforms, and sustainability orientation have emerged as equally important in strengthening competitiveness and resilience.

Digital transformation has a multidimensional impact on Moroccan supply chains. It enhances efficiency by streamlining processes, improves visibility and traceability, and increases agility in responding to market fluctuations and disruptions. Furthermore, it strengthens integration and collaboration across stakeholders, fosters customer satisfaction, and contributes to competitiveness. However, the analysis also reveals that these impacts are not uniform, and their effectiveness depends on firms' readiness and resource availability.

The benefits of digital transformation include cost reduction, enhanced visibility, improved customer service, and alignment with sustainability goals. Yet, these are counterbalanced by significant challenges such as high implementation costs, limited digital infrastructure, skills shortages, resistance to change, and cybersecurity risks. These findings highlight the dual nature of digitalization, offering both opportunities for innovation and barriers that need to be addressed for Moroccan companies to fully realize its potential. In sum, this research demonstrates that supply chain performance in Morocco is at a transition point, where traditional performance levers coexist with new digital imperatives. The future of Moroccan supply chains will depend on the ability of firms and policymakers to overcome structural barriers and leverage digital tools strategically to build more resilient, agile, and competitive supply chains.

At the same time, the context-specific focus on Morocco represents both a strength and a limitation of this research. On the one hand, concentrating on an emerging economy provides rich, grounded insights into how digital transformation unfolds in environments characterized by infrastructural constraints, SME dominance, and evolving institutional frameworks. This contextual depth enhances the relevance of the findings for policymakers and practitioners operating in similar developing settings. On the other hand, the specificity of the Moroccan economic, regulatory, and industrial landscape may limit the direct generalizability of the results to other regions or highly industrialized economies. Differences in technological maturity, supply chain sophistication, digital infrastructure, and institutional support mechanisms could lead to distinct patterns of digital adoption and performance outcomes. Therefore, while the identified determinants and dual impacts of digital transformation may offer conceptual relevance beyond Morocco, their empirical validation in other industrial sectors and regional contexts remains necessary. Future comparative studies across emerging and developed economies would help assess the transferability and robustness of the proposed insights and framework.

4.1 Implications of the study

4.1.1 Theoretical implications

This study makes several important theoretical contributions to the literature on supply chain management in emerging economies. First, it proposes a new framework of determinants of supply chain performance (SCP) within the Moroccan context. While previous studies in Morocco have primarily focused on operational indicators such as logistics costs, inventory levels, and delivery times, the present research expands this perspective by integrating digital-era factors. These include real-time information sharing, forecasting and predictive capabilities, digital integration, and sustainability orientation. By doing so, the study bridges traditional efficiency-based approaches with the emerging digital and sustainability imperatives that increasingly shape supply chain performance.

Second, the study contributes to theory by analyzing the multidimensional impacts of digital transformation on SCP. It highlights that digitalization not only improves efficiency and visibility but also fosters agility, integration, and customer satisfaction. At the same time, the research reveals the dual nature of digital transformation: while it provides opportunities for competitiveness and resilience, it also introduces challenges such as high costs, digital infrastructure gaps, and organizational resistance. This nuanced view advances the theoretical debate by showing that digital transformation in emerging economies is not a linear process of improvement but rather a context-dependent phenomenon with both enabling and constraining effects.

Finally, by situating these findings within the Moroccan context, where empirical evidence remains limited, this study contributes to filling the theoretical gap on supply chain performance in developing countries. It enriches the global literature by offering evidence from an underexplored setting, thereby expanding the applicability of supply chain theories to diverse economic environments.

4.1.2 Implications for policy makers

The findings of this study also provide important implications for policymakers, particularly in developing countries where structural constraints often limit the effectiveness of supply chain transformation initiatives. First, the results underscore the need for investment in digital infrastructure—including reliable internet connectivity, cloud systems, and data platforms—since these are prerequisites for the successful adoption of digital supply chain solutions. Without adequate infrastructure, companies may remain unable to benefit from the efficiency, agility, and resilience that digital transformation offers.

Second, policymakers should prioritize capacity-building programs aimed at improving digital literacy and technical skills among supply chain professionals. The study shows that skills shortages and lack of training are major barriers to leveraging digital tools. National strategies that promote continuous training, certification programs, and partnerships with universities and business schools can help bridge this gap.

Third, the study highlights the importance of regulatory and institutional frameworks to support digital adoption. Policymakers in developing countries should design clear guidelines on data protection, cybersecurity, and interoperability standards, ensuring that firms can engage in digitalization with confidence. In addition, providing fiscal incentives, subsidies, or public–private partnerships could ease the burden of high implementation costs, especially for SMEs.

Finally, beyond efficiency and competitiveness, the findings stress the opportunity for policymakers to promote sustainable supply chain practices by encouraging firms to align digital initiatives with environmental and social responsibility goals. This dual focus on digitalization and sustainability can help developing countries not only modernize their supply chains but also integrate into global value chains in a more resilient and responsible manner.

4.1.3 Implications for companies

For companies, the results of this study offer several practical implications for strengthening supply chain performance in the digital era. First, firms should recognize that digital transformation is not only a technological investment but also a strategic process that requires organizational alignment, cultural change, and capacity building. Embracing digital tools such as ERP systems, IoT devices, and AI-based forecasting solutions can significantly improve visibility, responsiveness, and decision-making, but their successful adoption depends on leadership commitment and employee engagement.

Second, the study highlights the importance of integrating digital initiatives with core supply chain practices. Companies should not treat digital transformation as an isolated project but as a means of optimizing stock management, delivery performance, procurement, and customer service. Aligning digital tools with operational objectives ensures that investments generate tangible performance gains.

Third, the findings show that resilience and risk management must be central considerations for companies in Morocco. Firms should use digital platforms to anticipate disruptions, manage uncertainties, and enhance agility, especially given the volatility of global supply chains. This requires developing partnerships with suppliers and customers that are supported by transparent information sharing and collaborative platforms. Finally, companies should view digital transformation as an opportunity to differentiate through sustainability and innovation. Integrating eco-efficient practices, improving traceability, and aligning with corporate social responsibility (CSR) expectations can enhance competitiveness in both local and international markets. In doing so, Moroccan firms can move beyond cost reduction and efficiency toward building more adaptive, innovative, and future-ready supply chains.

4.1.4 Limitations and future research directions

Like any research, this study is subject to certain limitations that need to be acknowledged. First, the study is purely qualitative in nature, which, while appropriate for exploring an emerging topic and context, does not allow for the generalization of findings to the wider population of Moroccan companies. Nevertheless, this limitation also constitutes one of the study's strengths, as it offers original insights into a relatively unexplored field and provides a foundation for future empirical work.

Second, the number of interviews was limited to 30 experts and specialists, reflecting the scarcity of expertise in supply chain performance and digital transformation within the Moroccan context. Although the sample provided rich and diverse perspectives, a larger pool of participants might have yielded additional insights and broader validation of the findings.

For future research, it would be valuable to build on these exploratory results by developing a conceptual framework of the determinants and impacts of supply chain performance in the digital era. Such a model could then be tested empirically using quantitative methods, with data collected directly from companies across different sectors. This would

allow for statistical validation of the relationships identified in this study and a deeper understanding of how digital transformation shapes supply chain performance in Morocco and other developing countries.

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Humanitarian logistics network design for emergency temporary shelters: a Brown-Gibson and p-median optimization approach

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<https://doi.org/10.22306/al.v13i3.800>**Humanitarian logistics network design for emergency temporary shelters:
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Abstract: The effects of climate change have impacted the whole planet, and although it is certain that losses in infrastructure have cost millions of dollars, what is most worrying is the millions of lives lost; specially in countries such as Mexico. In Mexico, the municipalities of the capital region of the state of Veracruz have been strongly affected by extreme meteorological phenomena, which on several occasions have led to temporary relocation of those affected. Unfortunately, no contingency plan that considers the location of temporary shelters has been proposed. For this reason, the objective of this study is to design of a Network for Temporary Shelters with four nodes by combining a technique with various criteria and an optimization model that not only allows for locating the municipality that would form part of the network through a minimum distance travelled, but also have the characteristics that would allow for safe quality accommodations for those affected in the capital region of Veracruz. The results show that the municipalities of Teocelo, Jalcomulco, Las Vigas Ramírez and Xico have the best conditions to form this network.

1 Introduction

Climate change is the modification of the temperature and the rest of the climate variables. Its effects have been felt worldwide and constitute the largest environmental threat that humanity faces. The North and South poles are melting, which is provoking a rise in the sea level worldwide. The impacts of climate change are unequivocal, it is the largest threat for world health, its effects are direct (heat waves, floods, droughts, etc.) and indirect (respiratory diseases, food insecurity, water, etc.). The socially marginalized are one of the most vulnerable groups affected by these risks. The occurrence of an extreme event or multiple extreme events can cause a catastrophic disaster. In some zones, weather phenomena are increasingly frequent, and in others, intense heat waves and droughts are registered [1-4]. According to [5], the four natural disasters that marked the last 100 years were: **1.** The flooding of the Yangtze River, China, in 1931; **2.** The Indian Ocean tsunami of 2004, which affected India, Indonesia, the Maldives, Sri Lanka, and Thailand, among other countries; **3.** Hurricane Katrina in 2005 devastated the southeastern United States, and **4.** The 2010 earthquake in Haiti, which practically destroyed the country. In this sense, logistic activity has become more relevant worldwide, not just in business and industrial areas, but socially as well. It can be said that *logistics* is the tool through which an effective and efficient resource and information flow can be achieved, integrated with activities along the supply chain with the objective of strengthening and increasing levels of customer service. The logistics field has the denomination of *humanitarian logistics* (HL), which is derived from the concern of looking for solutions for diverse problems, such as those related to *climate change* and its presence, impact, and the frequency of extreme natural phenomena, which has been of interest to governments, organizations, and researchers worldwide [6].

In this area, a shelter is understood as a synonym for an asylum designated for reception or support. When a person is given or assigned one, it not only provides a roof for protection against the elements, minimize the risk of illness or even death, but it is also a place where an individual recovers his or her dignity. In general there are three types of shelter: *a)* emergency, designed for emergency situations, which tend to be tents or prefabricated buildings; *b)* transition, made with more resistant materials for rain or cold, used for refugee camps; *c)* durable, more independent, solid, and better equipped than the first two, which are given to refugees that have been in the host country for many years [7]. In Mexico, the

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General Law of Civil Protection [LGPC] (2023) mentions that a temporary shelter is the physical installation authorized to give temporary protection and well-being to people without immediate possibilities of access to a safe room in case of imminent risk, emergency, catastrophe, or danger [8].

1.1 Mexico facing climate change

Climate change will generate larger impacts on human beings, mainly in the areas of extreme poverty and where there are high risks of extreme weather phenomena such as prolonged droughts or torrential rains. Mexico is situated in the southern part of North America and is adjoined to the United States in the north, the Gulf of Mexico in the east, Belize and Guatemala in the south, and the Pacific Ocean to the west. It has a surface of 1,972,550 km², divided into 32 federal entities, and has a population of 129 million people according to the National Institute of Statistics and Geography [INEGI] 2023 [9].

The geographical and social characteristics of Mexico make it one of the most vulnerable countries to climate change in the world. Due to its location between two oceans as well as its latitude and slopes, it is exposed to different weather phenomena. A determining factor of its social vulnerability is poverty, and the social and environmental impact generated by extreme weather phenomena also affects the economy [10]. Among the natural phenomena over the last ten years are the events mentioned below in Table 1.

Table 1 Natural phenomena in Mexico [11-20]

Date	Phenomenon	States affected
2015	Hurricane Patricia	Michoacán, Colima, Jalisco and Nayarit
2016	Tropical Storm Earl	Veracruz, Hidalgo and Puebla
2017	Earthquake magnitude 7.1	Puebla, Ciudad de México, Morelos, Estado de México, Guerrero, Oaxaca and Tlaxcala
2018	Earthquake 7.2	Oaxaca, Ciudad de México, Estado de México, Guerrero and Morelos
2019	Earthquake 6.7	Chiapas and Hidalgo
2020	Inundaciones en el sureste	Campeche, Tabasco, Veracruz,
2021	Inundaciones del Río Tula	Hidalgo
2022	Hurricane Agatha	Veracruz, Oaxaca, Chiapas and Tabasco
2023	Hurricane Otis	Suroeste de México, Guerrero
2024	Hurricane John	Colima, Michoacán, Oaxaca and Guerrero

1.1.1 Explanation of the problem

The state of Veracruz (of Ignacio de la Llave) is one of the 32 states that makes up the country of Mexico (31 free and sovereign states and Mexico City), located in the eastern part of the country, it is adjoined to Tamaulipas and the Gulf of Mexico in the north, Chiapas and Tabasco to the south, and Puebla, Hidalgo, and San Luis Potosí to the west. It represents 3.7% of the total national surface area. Figure 1 shows the location of Veracruz inside of Mexico.



Figure 1 The state of Veracruz (of Ignacio de la Llave) [21]

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Veracruz is made up of 212 municipalities that are inside ten regions [22,23]. In Figure 2, we can observe these regions.



Figure 2 Regions of the state of Veracruz (of Ignacio de la Llave) [24]

The Capital region is located in the central part of Veracruz. It extends over a surface of 5,568.55 km² and is integrated into 33 municipalities, Acajete, Acatlán, Actopan, Alto Lucero de Gutiérrez Barrios, Altotonga, Apazapan, Ayahualulco, Banderilla, Coacoatzintla, Coatepec, Cosautlán de Carvajal, Chiconquiaco, Emiliano Zapata, Ixhuacán de los Reyes, Jalancingo, Jalcomulco, Jilotepec, Landero y Coss, Miahuatlán, Las Minas, Naolinco, Perote, Rafael Lucio, Tatatila, Teocelo, Tepetlán, Tlacolulan, Tlalnelhuayocan, Tonayán, Las Vigas de Ramírez, Villa Aldama, Xalapa and Xico. There is a high degree of marginalization in 48.48% of its municipalities, low marginalization in 6.06%; medium marginalization in 36.36%; very high marginalization in 3.03%, and very low marginalization in 6.06%, according to the National Council for the Evaluation of Social Development Policy (2015) [25].

In the last ten years, the Capital region has declared disasters by means of the National Center for the Prevention of Disasters [CENAPRED] [26], since it has been significantly affected by weather phenomena. 75% of its municipalities have declared at least one disaster. Despite this, there is no contingency plan to help the government effectively determine the best location of temporary shelters to provide protection and relief to those affected by emergencies or disasters [27]. Thus, the objective of this work is to propose the creation of an Emergency Temporary Shelter Network (ETSN) made up of four nodes, to accommodate people affected by weather events in the region. For this, we use the Brown & Gibson model for multi-attribute decision making. From the results, an adjustment factor is used with the application of the p-median problem, with which we have created an ETSN with four nodes that are found at minimum traveled distances and with appropriate characteristics to shelter people affected by a weather event.

This study is divided from this paragraph into a) the state of art, which carries out a literature review regarding the location of emergency facilities, as well as literature regarding the Brown & Gibson model for multi-attribute decision making and the application of the p-median problem, b) methodology, made up of three phases, in this section we carry out data collection and the application of location methods and the results obtained through each one of these, and c) results and discussion, which gives a comparison of the obtained results to locate facilities in the state of Veracruz, d) conclusions, which presents the discoveries found by the authors, and e) references that show the bibliographical sources used as a resource for answers for this explanation.

1.2 Literature review

In this section, we show the revision of the literature of the methods, techniques, and methodologies used by different researchers to give answers to the location problem regarding humanitarian logistics, as well as literature about the methods used for creating the ETSN.

1.2.1 Methodologies, methods, and techniques of the problem of facility location

In the following paragraphs, we present research regarding the subject of humanitarian logistics, specifically installing temporary shelters worldwide.

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Researchers [28] presented a Mixed Integer Linear Programming model to solve the problem of shelter location in the midst of uncertainty in Turkey, and the results showed that with different combinations, the factors of rate of shelter use, service level of demand, and demand pattern lead to completely different solutions. In the same way, the research document [29] proposes the design of shelter networks through a methodology based on risk (population, shelter, and evacuation). In Haiti, the results guaranteed the efficiency of the model in a real context. Likewise, the researchers [30] developed a multi-objective shelter location and relocation model in the midst of uncertainty in case of an earthquake evaluated in different scenarios. It is worth mentioning the work of [31], where researchers carried out a study regarding shelter location and assigning the affected population shelters with a mixed-integer stochastic programming model in three stages to simulate the real environment of an earthquake.

Continuing with this analysis, it is worth mentioning the work of [32], in which the authors developed a multi-objective multi-period with multi-sourcing model, which determines the location of logistics centers in a disaster, implements a fuzzy factor evaluation system under the condition of making decisions in groups in order to determine weights, the results provided great managerial perspectives for the decision makers. Likewise, the work of [33] presents a fuzzy additive weighting system to resolve facility location problems through subjective and objective attributes, under the condition of making group decisions, and it numerically gives examples of the procedure. The researchers [34] propose a multi-objective optimization model to determine the location in response to the logistics of humanitarian help using the Epsilon-Delta limit method and programming objectives for its resolution. The validation of the model is carried out using a case study in Thailand.

Some researchers have been reviewing the literature regarding the location of humanitarian logistics facilities by means of techniques, methodologies, and tools used to give a solution to specific problems as well as global problems. In some studies elements are proposed that should be considered to minimize risks and guarantee quality of life for people affected, such as in the case of researchers [35], who carried out a literature review about the location of humanitarian facilities for a period of three years, signaling that the revised studies are normally adjusted to the following realities; 1. Capacity limit; 2. Stochastic models; 3. Locations that are not pre-defined; 4. Deprivation and multi-objective functions. They recommend that in future investigations aspects such as facility temporality, robust models, routing with restrictions, etc. should be included. The work of [27] gives a temporary shelter network evaluation framework through critical indicators of coverage performance and relevant services. The results of the evaluation show the need to take measures to alleviate shelters that, due to their location, can be overfilled.

It should be noted that the literature review did not find any articles proposing the design of an ETSN in the capital region of Veracruz that combines the Brown-Gibson and P-median or any other location methods. This gap constitutes the main contribution of this research.

1.2.2 Literature review of facility location methods Brown-Gibson and p-median

The following describes the literature relevant to methods used for the creation of ETSN.

Brown-Gibson method

The Brown-Gibson location model is a location model of one site with multiple attributes, it deals with the disadvantages associated with qualitative and quantitative methods and considers types of factors or criteria, objective and subjective. The first ones determine if a location is considered for an additional evaluation, the objective factors are the translation in monetary terms, while the subjective ones are qualitative measures. The model that integrates the three categories in this way is presented in equation (1) [36]:

$$LM_i = CFM_i [\alpha \times OFM_i + (1 - \alpha) \times SFM_i], \quad i = 1, 2, \dots, m, \quad (1)$$

Where:

CFI_{ij} : critical factor index for location i regarding the critical factor CF_j , takes value 1 if location i fulfills the requirement of critical factor CF_j , and 0 in the opposite case.

α : is the weight of the objective factor decision, it should be between 0 and 1.

OFM_i : relative value of the objective factors for location i , it is based on the cost.

SFM_i : relative value of the subjective factors for location i , it is found in the 0-1 scale.

LM_i : the best location for the plant is the one which has the highest location measurement.

P-median method

The facility location problem arises when deciding where the facilities should go, guaranteeing client satisfaction [37]. In the same way, the p-median model looks to locate “p” facilities in a way that minimizes the distance between the nodes that have a demand and the designated facilities. The model is described in the following paragraphs.

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Parameters:

$J = \{1, \dots, n\}$ index group for clients

$N = \{1, \dots, m\}$ index group for the location of the averages

$J = N$ for each $(j, i), j \in N, i \in J$

Variables

W_j = total demand to cover the node j ;

C_{ij} = distance from the node j to the node i ;

P = number of facilities to locate;

Y_i = takes the value one if an installation is located at i y 0 otherwise.

X_{ji} = takes the value one if an installation is located at i y 0 otherwise.

Mathematical Formulation

The mathematical formulation of the problem is presented in the following way:

$$\text{Min} = \sum_{i \in J} \sum_{j \in N} W_j C_{ji} X_{ji} \quad (2)$$

Subject to

$$\sum_{i \in J} X_{ji} = 1 \quad \forall j \in N \quad (3)$$

$$\sum_{i \in J} Y_i = P \quad (4)$$

$$X_{ij} \leq Y_i \quad \forall j \in N, i \in J \quad (5)$$

$$X_{ji} \in \{0,1\}, Y_i \in \{0,1\} \quad \forall j \in N, i \in J \quad (6)$$

Equation (2) represents the objective function, minimizing the sum considered for distances associated with the nodes of the client municipalities assigned to the nodes of the candidate municipalities. Equation (3) guarantees that all the client municipalities have a precise location. Equation (4) establishes the number of facilities in P . Equation (5) prohibits assigning a site without facilities, which means only nodes with facilities will supply the product. Equation (6) reinforces the binary nature of the decisions for installing a node and assigning a node a facility for a client municipality [38].

2 Methodology

Figure 3 shows the methodology used for the implementation of an emergency temporary shelter network in the state of Veracruz, especially in the Capital region. The methodology starts with the collection, analysis, and selection of the information to make way for the application of the first facility location method called Brown & Gibson, or Synergetic. With this, the priority load that has the municipalities contained in the region to be able to form part of the humanitarian shelter network will be obtained. Once the Synergetic method is applied, it makes way for the programming and application of the classic p-median problem with Lingo 21.0® software and the results will be shown on graphs.

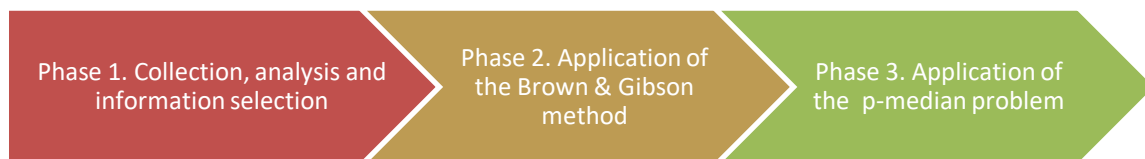


Figure 3 Methodology to solve the facility location problem

2.1 Phase 1 - collection, analysis and information selection

To carry out the application of the proposed methods, different databases with information from each one should be developed, the information used and the reference source is below.

2.1.1 Synergetic method

1. *Critical factors* are those elements considered essential for an organization to function, in this case the functioning of a humanitarian shelter, one determining critical factor is:
 1. *Municipalities that have declared a hydrometeorological weather phenomena disaster in the last 10 years.* The information will be used as a probability factor for a municipality with a high impact factor to be

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disregarded in forming a humanitarian shelter network. For this step, we can refer to the National Center of the Prevention of Natural Disasters website (CENAPRED).

2. *Objective factors*, the objective factors allude to measurable and quantifiable criteria, in the case of the temporary shelter study, the factors considered are:
 1. *Provisioning*, two sites of shops of social interest were considered as suppliers for people affected in temporary shelters, located in the municipalities of Puente Nacional and Villa Aldama and the cost of fuel to move the supplies to the temporary shelters was calculated, the cost estimated was \$1 MXP per km. The data were obtained through the Google Maps® application.
 2. *Attention to health*, with the objective of providing the medical attention necessary to people affected by weather phenomena, the cost of taking medical equipment to screen, vaccinate, and evaluate affected people was considered, the cost of fuel to move the supplies to the temporary shelters was calculated, the cost estimated was \$1 MXP per km. The attention points considered were the Speciality Regional Hospital of Veracruz and the Regional Hospital of Xalapa. The data were obtained through the Google Maps® application.
 3. *Active shelters for the state government*, the Civil Protection Department shows a series of temporary shelters located in different municipalities, this factor was considered since the cost of reusing a shelter would be reduced, as it would already have the conditions necessary, as opposed to opening a new shelter. The more shelters a municipality has, the higher the capacity could potentially be. The information is taken from [39].
3. *Subjective factors* are qualitative elements based on perception and evaluated with a scale. The factors considered are listed below:
 1. *Degree of marginalization (60%)*, marginalization is a multi-dimensional and structural phenomenon which originates from the economic production model expressed in the unequal distribution of progress, in the productive structure, and in the exclusion of diverse social groups, in the process as well as the benefits of development [40]. The higher the marginalization, the higher the costs would be for a municipality to form part of the ETSN.
 2. *Insecurity (40%)*, the perception of security looks to measure the perception of public security that the population and homes have where they reside, as well as crime rate [41]. Gleaned from information obtained on page [37], rubrics such as damage to property, breach of trust, threats, dispossession, extortion, domestic violence, gender violence, home invasion, robbery, and other more unusual crimes, the increase in reports in 2024-2025 of property damage was considered for this evaluation.

2.2 Phase 2 - application of the Brown-Gibson method

1. Critical factors from the information obtained in Phase 1 was included in Table 2, which shows an extract from the evaluation table that determines which municipalities continue to be evaluated and which will be disregarded.

Table 2 Critical factors

Critical factor / Municipality	Acajete	Banderilla	Emiliano Zapata	Jalancingo	Las Ram3rez	Vigas Aldama	Xico
Disaster declared in the last 10 years	0	0	1	0	1	1	0
Remove (R)	R	R	K	R	K	K	R
Keep (K)							

The municipalities which will continue to be evaluated with the Synergetic method will be eight:

- a) Emiliano Zapata; b) Ixhuac3n de los Reyes; c) Jalcomulco; d) Las Minas;
e) Las Vigas Ram3rez; f) Teocelo; g) Villa Aldama, and h) Xico.

2. To give continuity to the synergetic method, Table 3 shows the objective factors used.

Table 3 Objective factors

Objective Factor / Municipality	Emiliano Zapata	Ixhuac3n de los Reyes	Jalcomulco	Las Minas	Las Vigas Ram3rez	Teocelo	Villa Aldama	Xico
Provisioning 1	23.70	107.00	39.90	110.00	92.00	78.20	101.00	74.60
Provisioning 2	87.90	54.90	86.90	22.60	16.20	73.30	0.00	69.70
Health Services 1	75.20	158.00	95.00	161.00	143.00	131.00	153.00	128.00

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Health Services 2	42.70	54.50	39.20	58.80	39.60	25.80	50.50	22.10
Active shelters	16	02	03	12	03	02	00	04

The results show that the municipality of Emiliano Zapata would incur the lowest installation costs, followed by Jalcomulco and Xico.

- To validate the subjective factors (Table 4), the marginalization factor and the perception of insecurity in the area are considered.

Table 4 Subjective factors

Objective Municipality	Factor	/ Emiliano Zapata	Ixhuacán de Reyes	los Jalcomulco	Las Minas	Las Vigas Ramírez	Teocelo	Villa Aldama	Xico
Marginalization Level		Very low	High	Medium	High	Medium	Low	Medium	Low
Increase in insecurity		9.33	0.00	0.00	0.00	0.00	0.00	0.00	+66.7

The results show that the municipality of Teocelo has the highest possibility of being chosen, followed by the municipalities of Jalcomulco and Las Vegas Ramirez.

- Applying the objective and subjective factors importance levels of 60% and 40% respectively, the formula is applied to obtain the Measurement of Location Preference, obtaining the results of Table 5.

Table 5 Measurement of location preference

Emiliano Zapata	Ixhuacán de los Reyes	Jalcomulco	Las Minas	Las Vigas Ramírez	Teocelo	Villa Aldama	Xico
0.1545	0.1360	0.1373	0.1360	0.1373	0.1386	0.1373	0.049

Figure 4 shows in red the municipalities disregarded during the first stage of the Synergetic process and in blue the municipalities that have the possibility of being the site of a temporary shelter.

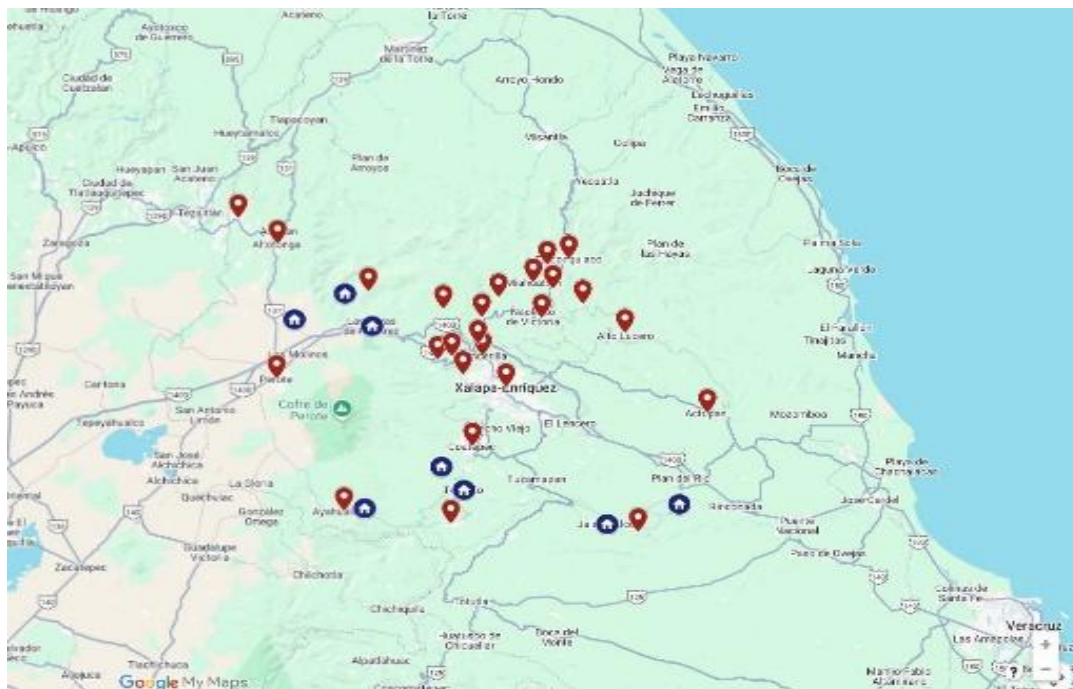


Figure 4 Resulting municipalities of the Brown-Gibson method, extracted through Google My Maps®

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From the above results, the application of the p-median problem was carried out, which will have the importance that not only allows for the minimum distance traveled, but also characterization of the zone in order to form part of the ETSN, using as a base the first term of the mathematical model of the Barojas-Payán et al. investigation [42].

2.3 Phase 3 - application of the p-median problem, with weight

Before carrying out the p-median problem with load, a trip with no load was carried out obtaining the 4 municipalities required as sites for temporary shelters to form the ETSN: a) Banderilla, b) Naolinco, c) Tatatila, and d) Teocelo. As can be observed, due to the restriction established in the present study case, the only municipality that can form part of the ETSN would be that of Teocelo, Figure 5 shows the municipalities mentioned in yellow, in blue, those obtained with the Synergetic method, in red, the municipalities that have resisted a disaster in the last 10 years, as well as Teocelo with a yellow pin with a protection symbol.

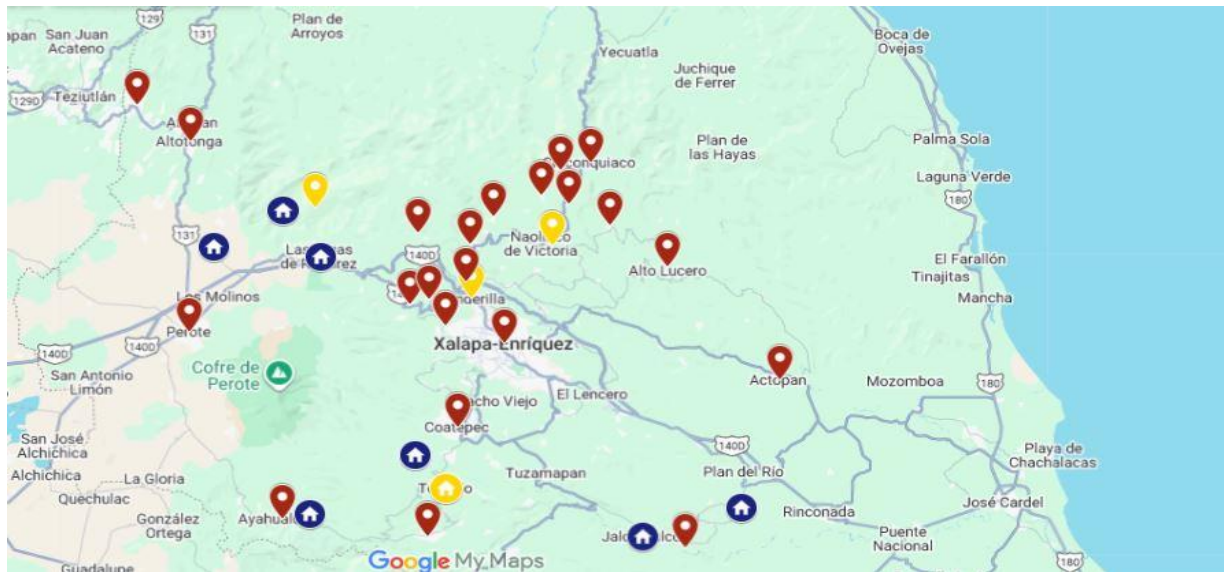


Figure 5 P-median with no load, extracted from Google My Maps®

During the application of the p-median model with a load, four municipalities were disregarded from the system, Acatlán, Banderilla, Altotonga, and Actopan, due to declaration of disasters. Figure 6 shows the colors 1. Red, municipalities disregarded in the first synergy stage and that also have been affected by natural phenomena in the last ten years; 2. Yellow, municipalities disregarded during the p-median application process due to their characteristics; 3. Blue, municipalities obtained with the Brown-Gibson method and that do not form part of the ETSN, and 4. Green, the municipalities that will form part of the ETSN, a) Jalcomulco; b) Las Vigas Ramírez; c) Teocelo, and d) Xico.

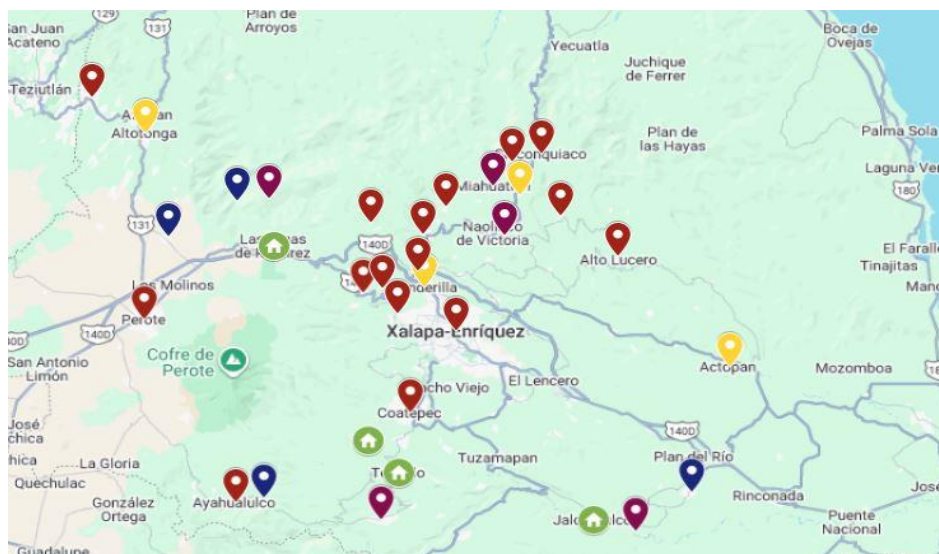


Figure 6 P-median with load, extracted from Google My Maps®

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3 Results and discussion

Table 6 presents the results through each one of the employed methods. The Synergetic method gives 8 municipalities with characteristics that allow for temporary shelters, however, the costs to provide supplies and services to those affected would be disproportionate. With the p-median method, the municipalities with the minimum distance traveled to the impacted municipalities is obtained, however, 75% of them do not fulfill the criteria of not having declared an emergency in the last ten years. Finally, the p-median method with a load allows us to have the four municipalities that will form part of the ETSN. It is worth mentioning that the municipality of Teocelo is the only one that fulfills the characteristics that each one of the methods looks for in a location.

Table 6 Location results

Method	Brown-Gibson	p-median	p-median with load
Resulting Municipalities	Emiliano Zapata	Teocelo	Teocelo
	Teocelo		
	Jalcomulco		
	Las Vigas Ramírez		
	Villa Aldama		
	Las Minas		
	Ixhuacán de los Reyes		
Disregarded Municipalities	Xico	Banderilla	Xico
			Banderilla
		Naolinco	
		Tatatila	
			Acatlán
			Altotonga
			Actopan

The facility location problem considers not only the costs of the establishment, but also the service; these two elements are fundamental to making decisions about the location of the facilities and who will provide the services. Regarding natural disasters, the uncertainty of the optimal location increases due to the level and area of impact of the phenomenon. After going through the literature, the temporary shelter network proposal for the Capital region of the state of Veracruz has not been found, however, in the work of [43], the p-median problem was used to establish three shelters in the municipality of La Perla Veracruz. What differentiates both investigations is the additional characterization carried out in this document, that although it is not the minimum distance traveled, it does have considerable municipal conditions for a temporary shelter.

4 Conclusions

The increase in temperatures has brought with it the presence of more frequent and impactful weather phenomena. Climate change is the biggest threat to world health and socially marginalized people are one of the most vulnerable sectors to its risks. The state of Veracruz is one of the Mexican states with the largest amount of weather phenomena, the Capital region specifically has been strongly affected by these events on many occasions and had temporary relocation of people affected. The document presents the design of an Emergency Temporary Shelter Network with four nodes with the combination of the Brown & Gibson Method and the p-median problem, which not only allows for the location of the municipalities that will form part of the network by means of a minimum traveled distance, but also has the characteristics that allow for quality accommodations for people affected in the capital region of the state of Veracruz. The results indicate that the municipalities of Teocelo, Jalcomulco, Las Vigas Ramírez, and Xico are the components of the ETSN. Future research will look to geographically extend the radius of the study and include more elements that allow for the formation of a complete humanitarian logistic network with stockpile centers, pre-positioned warehouses, levels of inventory, and vehicle routing.

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Blockchain-enabled business intelligence for strategic agility in logistics information flows: the mediating role of data transparency

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TR-10 Mersin, 990 10, Turkey, ORCID 0000-0001-5753-6162, msagsan@eul.edu.tr**Keywords:** logistics information flows, blockchain-enabled business intelligence, data transparency, strategic agility, SMEs.**Abstract:** This study examines how blockchain-enabled business intelligence (BEBI) strengthens strategic agility by improving the integrity and visibility of organizational information flows in small and medium-sized enterprises (SMEs). The addressed problem is that SMEs operating in dynamic markets often rely on analytics built on fragmented and unverifiable data, which weakens the speed and reliability of strategic responses across logistics-relevant flows (information, financial, and human flows). Using a questionnaire survey of 372 senior and middle managers and structural equation modeling with SmartPLS 4, the study tests a model linking BEBI, data transparency, and strategic agility. The results indicate that BEBI positively influences strategic agility and data transparency, and that data transparency positively affects strategic agility. Moreover, data transparency partially mediates the relationship between BEBI and strategic agility. The novelty of the study is the integration of blockchain-based trusted data architecture with business intelligence to explain how transparent, traceable, and reliable data flows enable faster sensing and reconfiguration of resources, supporting agile strategic actions in SMEs.

1 Introduction

This study, therefore, investigates how to manage logistics-relevant flows—especially the flow or management of information, the flow or management of financial resources, and human flows—while responding to rapid market turbulence [1,2]. In SMEs, strategic agility depends on the ability to sense changes quickly and coordinate decisions using trustworthy data flows that are traceable, visible, and resilient to manipulation [3]. This study, therefore, investigates the impact of blockchain-enabled business intelligence on strategic agility and tests whether data transparency explains this relationship [4,5].

Even though there is an emerging trend of increasing research being carried out on blockchain technology or business intelligence, there remains a substantial research gap pertaining to the combined effects of blockchain technology and business intelligence on strategic agility [6,7]. Most of the previous research on this topic has been carried out to identify the effects of blockchain technology or business intelligence [8,9]. Furthermore, there is also a need to explore the possible mechanisms involving the employment of blockchain technology in the enhancement of strategic performance [10]. The employment of data transparency as a mediator on the employment of analytical systems and strategic agility has lacked significance in the present literature, particularly in the emerging economies in which SMEs operate [11,12]. The issue of blockchain-based business intelligence and strategic agility, with an emphasis on data transparency, addresses the challenges faced in the context of the current study [13]. This paper shall test the hypothesis that transparent and accurate data environments have an effect on the flexibility of strategic agility in the Jordanian SME context [14,15].

The paper proposes a framework concerning blockchain, business intelligence, and strategic agility to add more rigor to the existing literature. Guidelines shall be constructed concerning new data technology and the strategic decision-maker to gain a better competitive advantage within the context of dynamic business environments.

2 Literature review

2.1 Blockchain-enabled business intelligence

A business intelligence solution based on the application of blockchain technology represents an advanced analytical solution that applies the principles of blockchain technology to existing business intelligence solutions [1,4]. The business

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intelligence solution based on blockchain technology is meant to upgrade the security, integrity, and real-time analysis capabilities associated with business data in an organization [6,15]. The business intelligence solution based on blockchain technology is distinct from other business intelligence setups in the sense that it applies the immutability characteristics of blockchain technology to enable business operations in an organization to have a high level of integrity [10,16]. The solution enables organizations to generate genuine business intelligence that can assist in organizational strategic-level decisions. From a strategic point of view, business intelligence systems based on blockchain technology can assist an organization in detecting any form of business environmental change with the help of clean and untampered-with data flows in an organizational setup [9,13]. The business intelligence system based on blockchain technology can assist in synchronizing business units in an organization in relation to organizational operations in a dynamic business setup to a greater extent, thereby emerging as a distinct strategic tool for enabling organizations to make fast decisions in a dynamic business setup [16,17].

2.2 Data transparency

Data transparency refers to the extent to which information within an organization is accurate, accessible, traceable, and understandable to selected authorized persons [18]. In blockchain technology-based networks, transparency is created by distributed architectures of information, which present a community view of information transactions, leading to lowered uncertainties and increased confidence in information application [10,12]. Data transparency at higher levels encourages faster validation of information, improvement in cooperation and collaboration, and reliance on analysis findings for sound decision-making [4,17]. Decision makers will be more willing to use analytics when they are confident of the information's clarity and accuracy. Data transparency is, therefore, an important integration mechanism that ensures analytics tools are integrated into the success of the strategic action plan [19,20].

2.3 Strategic agility

It is pertinent to note that the application of strategic agility is considered a feature of an organization that perceives changes in the surrounding setting and responds accordingly to such changes [9]. Within the digital platforms, an individual or an organization with strategic agility depends on the presence of timely, credible, and accessible information [21]. The application of blockchain technology to strategic agility allows an organization to gain insight based on information from transparent and credible data [10,22]. Organizations with access to credible data, therefore, have the capacity to enhance decision-making processes related to strategies and responsiveness to changes in the marketplace. Strategic agility, therefore, depends on both technology capabilities and data management [13].

2.4 Hypothesis development

Blockchain business intelligence could be a paradigm shift in business intelligence because trusted data architecture can be integrated with advanced business intelligence [13,22]. This study assumes that the integration of blockchain technology will enable the accuracy and definiteness of data employed within the business environment [3]. The decision-maker will be poised to feel the changes in the business environment through the use of precise business data [4,13]. Business organizations can adjust quickly to the changes within the business environment. There shall be no delay in business decision-making, in which business organizations are discouraged from making quick decisions [17]. This study assumes that business organizations will be agile because they can make quick analyses on alternatives or means allocation [12]. Alignment within the business environment will be important because the study has been able to assume the following:

H1: Blockchain-enabled business intelligence has a positive impact on strategic agility.

Blockchain-based business intelligence has made a big impact on the transparency of data by combining the transparency and immutability of blockchain technology with business intelligence [12,18]. Blockchain technology makes sure that the origin of data can be traced, that all transactions can be traced, and that changes that occur with time can be traced as well [20,22]. Such transparency removes any gaps or errors that might occur as a result of segregating data. Business intelligence with transparency enables managers or decision-makers to view data related to the flow of data, as well as data provided by the analysis [6,14]. The transparent nature of the information environment facilitates collaboration [7,15]. Thus, blockchain-based business intelligence establishes transparency in credible information processes [20]. The reasoning outlined above has permitted this study to propose the following assumptions:

H2: Blockchain-enabled business intelligence has a positive impact on data transparency.

Data transparency is considered a basic requirement in productive strategic decision-making in today's organizations. If data is transparent, it means that the decision-makers have accurate, complete, and consistent information at their command [10]. This allows organizations to monitor their operations on a constant basis [6]. Organizations will be able to detect opportunities and threats that arise. This is a basic issue in organizations that require proactive strategic action

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[31]. Organizations will be in a position to synchronize their operations with the demands of the environment. This is necessarily a result of data transparency [10,32].

Moreover, data transparency promotes cooperation and communication between units in an organization. These are important elements in forming strategic agility [9]. Sharing one and the same verified information between all stakeholders of an organization leads to increased cooperation and harmonization of strategic moves [13,16]. Data transparency fosters a constant process of organizational learning. This results in agile strategic moves and innovations [19,21]. Therefore, apart from promoting faster decision-making, data transparency leads to higher-quality strategic moves. On this logic, the study assumption is as follows:

H3: Data transparency has a positive influence on strategic agility.

Though blockchain-based business intelligence provides an enhanced level of analytics and predictability, the role of such business intelligence in facilitating strategic agility is dependent upon the interpretation and trust maintained by the organizations in the results obtained through the system [26,32]. Strategic agility in business cannot be achieved through enhanced analytical and predictable solutions if the results are not trusted or if the sources of the data are not transparent to the organization [16,20]. Data transparency covers the factor of trust and enables the results to be traceable and verified.

Moreover, data transparency serves as an essential explanation for the connection between technology adoption and strategic outcomes [11,17]. The adoption of blockchain-based business intelligence improves data transparency through real-time visibility and incorruptible data entries. If data transparency is higher, organizations are more ready to adopt the findings produced by analytical systems, which quickens strategic reactions and flexibility [17,20]. By the same token, low data transparency may reduce the efficacy of analytics, even when the technical systems employed are of a superior level of sophistication [18,21]. Therefore, data transparency is an explanation for and an underlying reason why blockchain-based business intelligence drives strategic agility rather than a direct technical consequence [10,15]. The study assumed the following based on this explanation:

H4: Data transparency positively mediates the relationship between blockchain-enabled business intelligence and strategic agility.

3 Methodology

3.1 Design

This research adopts a quantitative design to examine how blockchain-enabled business intelligence supports strategic agility through improved logistics information flows. The methodology focuses on the flow or management of information, financial flows, and human flows within SMEs, emphasizing how transparent and traceable data flows enable faster sensing, coordination, and strategic decision-making.

This research uses a quantitative research design to explore the strategic agility impact of blockchain-enabled business intelligence, using the mediating variable of data transparency. Quantitative research is appropriate for this study, as it allows the testing of hypotheses in relation to theoretical relationships between constructs, using statistical modeling. The research is cross-sectional, as it involves gathering data at one point to explore the research participants' perceptions of the research constructs within the organizational setting. The research takes place in the SMEs, which are known to have the following characteristics: data-intensive, technologically progressive, and using advanced digital technologies to make strategic decisions. The SME companies are an appropriate setting in which to conduct the research, as it involves the processing of substantial quantities of operating and customer data, and the trend in the industry is toward the use of blockchain and analysis technologies to increase strategic responsiveness and competitiveness.

3.2 Companies and sample

The population of interest in the research included SME firms operating in a competitive and digitally enabled space. Data were collected from 372 respondents who are in management positions within their companies. The candidates/target population have been considered due to the substantial application of BI systems and an increasing fascination with blockchain integration to enhance the clarity and decision-making potential of data in the different firms. The level of analysis in the research included the employees of the organization, specifically in positions concerning management and professionalism associated with IS, strategy, and decision-making. These candidates have been regarded as appropriate owing to their substantive involvement in the application and decision-making of BI systems within the organization of employment. Any form of purposive sampling is used to guarantee that the candidates have adequate experience and knowledge regarding the research constructs.

3.3 Pilot study

Before the initiation of the primary gathering of data, a pilot test is used to test the clarity, reliability, and validity of the measurement tool to be used within the study. In this case, the study carefully selected 28 respondents from the targeted population for the main study to participate in the pilot test. The study intentionally excluded these respondents

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from the final analysis to prevent bias in it. The primary objective of conducting a pilot test is to examine the wording of the items used in a questionnaire, point out any inconsistencies, and ensure a consistent understanding of the questions being asked in a given questionnaire by its respondents. In addition, reliability will be measured to ensure that all variables have an acceptable internal consistency before embarking on gathering data in relation to a study.

3.4 Measurement and data collection

The use of a structured questionnaire made it possible to conduct the measurement of the constructs related to the study in a manner fitting the research setting and purpose. All the measurement statements were posed using a five-point Likert scale ranging from "strongly disagree" to "strongly agree." The use of a Likert scale has been generally well accepted and adopted in various studies for the proper determination of the perceptual and behavioral elements. The measurement statements were adopted from other concrete and contemporary studies on related fields such as blockchain technology, business intelligence, data transparency, and strategic agility. The statements were specifically adapted to fit the organizational setting of the current research. Business intelligence achieved using blockchain technology was measured using a set of statements related to the integrity of the data, use of unalterable data sources, ability of results derived using analytical systems, and tracing the use of the data for analytical functions [1,4,6]. Data transparency was measured using the set of statements adopted to determine the traceability of the data sources, understanding of access to the organizational data, and consistency of the organizational information [23,24]. Strategic agility was measured using a set of statements adopted to determine the organizational responses to the various changes and adjustments, rapid decision-making on the organizational strategic plans, efficient reorganization of organizational resources, and adjustment of organizational strategies in accordance with the various market adjustments [9,10,13]. The measurement model has been instrumental in establishing both the internal consistency and the validity of the measures, establishing the suitability and accuracy of the current study on the desired aspects, and fitting this organizational setting.

Data acquisition and collection are carried out using a self-report survey questionnaire administered through an online platform to the participants in the SMEs' corporations. The online survey format allows for flexibility, especially when dealing with geographically dispersed participants for efficient responses. The survey administration is carried out voluntarily, and the participants are informed of the relevance of the research while assured that their confidentiality and anonymity are maintained. Prior consent from identifiable persons in organizational settings that require such consent prior to administration is sought by researchers. Follow-up notifications are also conducted to ensure effectiveness when responding to the survey questionnaires. The entire data collection process is conducted within a set time frame that gives adequate time for response without allowing time bias.

3.5 Analytical methodologies

Analysis of data was done using structural equation modeling with a focus on partial least squares structural equation modeling (PLS-SEM). Analysis using the PLS-SEM technique was essentially informed by the following characteristics surrounding the PLS-SEM method: There was a two-step procedure carried out in the analysis of the data. Firstly, it involves evaluating the measurement model to test the reliability and validity of constructs identified in the research design ex-post. Apart from examining internal-consistency reliability, discriminant validity, and convergent validity, it is followed by analyzing the structural model to test the validity of hypothesized relations between constructs identified in the research design ex-post. Afterward, the results of the structural model are analyzed to test the hypotheses and verify the validity of the relationships among the constructs identified in the ex-post research design. A mediating role of transparency in collected data is tested through analyzing direct and indirect relations between blockchain-based business intelligence and strategic agility in an organization. Bootstrapping techniques are utilized to determine significance in mediating roles identified in research ex post. This step renders empirical evidence in supporting or opposing identified hypotheses in research design and explaining relations between variables under study in ex-post research design [25].

4 Results and discussion

4.1 Sample characteristics

The following is a description of the demographic characteristics of the participants shown in Table 1. The research participants consist mostly of male respondents, reflecting their dominant role in data-intensive industries. Most respondents choose the option that categorizes them between the ages of 35 and 44 years, which represents over a decade of work experience, ensuring that the respondents mostly consist of experts and persons with experience. Most research participants take senior managerial positions, which provides reliable results, given that they closely take part in organizational decisions concerning blockchain-enabled business intelligence.

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Table 1 Demographic characteristics of the sample

Category	Frequency	Percentage (%)
Gender (Male)	241	64.8
Gender (Female)	131	35.2
Age (25-34 years)	98	26.3
Age (35-44 years)	164	44.1
Age (45 years and above)	110	29.6
Managerial Level (Middle)	156	41.9
Managerial Level (Senior)	216	58.1
Experience (5-10 years)	143	38.4
Experience (More than 10 years)	229	61.6

4.2 Descriptive statistics

The values contained within Table 2 illustrate the data descriptions of the variables studied. The mean score of each variable exceeds 4.00, recommending a general consistency among the study participants regarding the importance and adoption rate of blockchain-based business intelligence, data transparency, and strategic agility within their respective companies. Additionally, the relatively low values of the standard deviations indicate a degree of homogeneity among the study respondents' perceptions, hence enhancing the reliability of the collected data [25].

Table 2 Descriptive statistics of study variables

Construct	Mean	Standard Deviation
Blockchain-Enabled Business Intelligence (BEBI)	4.15	0.61
Data Transparency (DT)	4.08	0.66
Strategic Agility (SA)	4.21	0.58

4.3 Measurement model assessment

Results of reliability and convergent validity for the measurement model are put forth in Table 3. Alpha values are found to be between 0.88 and 0.91, and composite reliability values are found to be higher than 0.92 for all variables, thus establishing high reliability of the internal consistency of the scale. All indicator loadings are well above the proposed cut-off, thus establishing the reliability of the indicators and corroborating convergent validity. In addition to this, AVE values are well above the cut-off value of 0.50, hence establishing high convergent validity. Therefore, results have confirmed and established the reliability of the proposed measurement model and its appropriateness for further structural analysis using SmartPLS 4 [25].

Table 3 Reliability and validity analysis of constructs

Construct	Code	Measurement Item	Loading	Alpha	CR	AVE
Blockchain-Enabled Business Intelligence (BEBI)	BEBI1	Data integrity is ensured through Blockchain.	0.85	0.90	0.93	0.72
	BEBI2	Analytics relies on immutable data sources.	0.87			
	BEBI3	BI outputs are highly reliable.	0.84			
	BEBI4	Data traceability supports analytics.	0.86			
Data Transparency (DT)	DT1	Data sources are fully traceable.	0.83	0.88	0.92	0.70
	DT2	Data access is clear and verifiable.	0.85			
	DT3	Information is consistent across systems.	0.84			
Strategic Agility (SA)	SA1	The firm responds quickly to change.	0.86	0.91	0.94	0.75
	SA2	Strategic decisions are made rapidly.	0.88			
	SA3	Resources are reconfigured efficiently.	0.87			
	SA4	Strategy adapts proactively to markets.	0.85			

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The discriminant validity test is conducted as illustrated in Table 4. The square root of the average variance extracted (AVE) of each construct is greater than the correlation between constructs. This confirms that blockchain-enabled business intelligence, data transparency, and strategic agility are separate constructs, thus satisfying the conditions of discriminant validity [25].

Table 4 Discriminant validity (Fornell–Larcker criterion)

Construct	BEBI	DT	SA
Blockchain-Enabled Business Intelligence (BEBI)	0.85		
Data Transparency (DT)	0.63	0.84	
Strategic Agility (SA)	0.59	0.67	0.87

4.4 Structural model results

Table 5, results from the direct path test reveal that all proposed paths are positive and significant. The connection between blockchain-enabled business intelligence and strategic agility has been identified to produce a positive impact ($\beta = 0.34$, $p < 0.001$), thus indicating that greater levels of blockchain-enabled business intelligence lead to enhanced levels of strategic agility. In addition, blockchain-enabled business intelligence has been identified to create a strong positive impact on the variable of data transparency ($\beta = 0.57$, $p < 0.001$), thus highlighting its critical role in making the data more visible, authentic, and credible. Furthermore, the variable of data transparency has been identified to produce a strong positive impact on strategic agility ($\beta = 0.41$, $p < 0.001$), thus highlighting that the more transparent the data environments, the more flexible the organization [25].

Table 5 Path analysis results for direct hypotheses testing

Hypothesis	Path	β	t-value	p-value	Result
H1	BEBI $\rightarrow$ SA	0.34	6.21	<0.001	Supported
H2	BEBI $\rightarrow$ DT	0.57	10.04	<0.001	Supported
H3	DT $\rightarrow$ SA	0.41	7.58	<0.001	Supported

4.5 Mediation analysis

As evident from Table 6, the result for the mediation test reveals that there is a positive indirect effect of blockchain business intelligence on strategic agility that is partially mediated by data transparency ($\beta = 0.23$, $p < 0.001$). The findings reflect that there is a direct effect, indicating that data transparency partially mediates this relationship. Data transparency is a crucial factor in determining how blockchain business intelligence affects strategic agility [25].

Table 6 Mediation analysis results

Path	Indirect Effect (β)	t-value	p-value	Mediation Type
BEBI $\rightarrow$ DT $\rightarrow$ SA	0.23	6.02	<0.001	Partial Mediation

4.6 Model fit assessment

The fit statistics shown in Table 7 reveal a satisfactory fit model. The SRMR value (0.064) is well below the cut-off, thus validating a satisfactory fit model. The value of NFI (0.92) is above the minimum acceptable fit level; thus, a high level of comparative fit is achieved. Further, the chi-squared to degree of freedom (2.41) is below the acceptable level; thus, a satisfactory fit model is achieved [25].

Table 7 Model Fit indices

Index	Value	Threshold
SRMR	0.064	< 0.08
NFI	0.92	> 0.90
Chi-square/df	2.41	< 3.00

4.7 Discussion

From a logistics perspective, the findings emphasize that transparent information flows reduce uncertainty and support faster coordination of decisions across operational processes. The results show that blockchain-based business intelligence supports strategic agility in a positive way by improving the validity, credibility, and availability of data within an organization [26,27]. In its role of making data immutable and traceable, blockchain enhances the basis of strategic decision-making by allowing an organization to detect changes within its environment [8,12]. This finding largely

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supports modern theoretical assumptions suggesting that credible data plays a significant role in allowing an organization to achieve strategic agility [28,23]. Nonetheless, modern theoretical studies suggest otherwise because, in its current form, using blockchain-based BI does not necessarily result in an agile organization because of integration issues within a system based on scalability and strategic processes [13].

The findings also show that transparency of the data has a significant function in promoting flexibility in the area of strategy. The use of blockchain in transparency allows the decision-maker access to accurate and traceable data in a short time; therefore, flexibility and adaptability of the strategy are promoted [29,30]. However, recent research argues that too much flexibility might bring benefits together with some negative consequences [20]. For example, there might be an “information overload” problem. Moreover, flexibility might make the organization more exposed to “data risks of privacy” since the flow of the data is highly transparent [10,18].

Results also indicate that data transparency is an important mediator between blockchain-enabled business intelligence and strategic agility. This implies that the strategic worth of blockchain-enabled business intelligence is achieved not only by leveraging analytics but also by making such analytics readily accessible throughout the organization due to data transparency [27,31]. This is even as recent empirical work establishes that data transparency remains critical in achieving strategic agility, as supported by recent empirical work; however, there are challenges in maintaining such an environment in relation to blockchain technology strategic agility [16,22]. These include issues surrounding regulations and compatibility, as well as validating data.

Concluding, it is evident that the application of blockchain-based business intelligence is able to provide strategic agility in an organization primarily because of improved transparency in data [10,16]. Nonetheless, recent studies have indicated that strategic agility is significantly dependent on the organizational acumen of the firm in relation to its digitization and analytics acumen [2,23]. Should the alignment between these elements be flawed, likely, the potential of blockchain-based BI in creating strategic agility will not be fully actualized [21,32].

5 Conclusion and future research

In practical terms, SMEs can improve the flow or management of information and financial flows by adopting BEBI to increase traceability, visibility, and decision speed. This research question focused on examining how blockchain business intelligence impacts a firm’s strategic agility, particularly regarding data transparency in a Jordanian SME environment. The findings suggest a significant positive impact of business intelligence, coupled with blockchain technology, on a firm’s strategic agility, as this amalgamation of technologies boosts the reliability, accuracy, and authenticity of data, allowing a firm to notice and respond to turbulence within a short timeframe. The role of data transparency plays an essential part and makes a significant positive contribution to the positive impact of blockchain business intelligence, enabling a firm to adapt to a rapidly changing environment with its pliable processes of decision-making.

The findings of this study may contribute to the development of the theory of business intelligence and strategic agility by demonstrating how blockchain technology can enhance data clarity and its effect on strategic agility capabilities [23]. Furthermore, the findings of this study have managed to verify the significance of data clarity in playing the role of a mediator, hence explaining and refining contemporary theories associated with the adoption of technology and strategic agility in having a direct and clear relationship, with less weightage to the significance of ensuring clarity and cleanliness of data streams [21,32]. From a practical standpoint, this particular research work appears to be a reliable source of information for managers who are eager to use blockchain-based management intelligence to enhance managerial agility [17,27]. The implication of the conclusion derived from this research work indicates the need to wire in proper data governance systems and invest in blockchain technologies to enjoy better performance gains in business [28]. There is a need for focus on how to ensure the involvement of innovative strategies and to inculcate transparency in their business strategies to ensure adaptability in business for the benefit of various professionals working in the realm of business innovation strategies [29].

However, the contribution notwithstanding, there exist limitations that the study faces as well. Firstly, the cross-sectional study design that the research uses restricts the study from demonstrating the dynamics and causality existing between the perceptions. This study uses perceptual variables that can be prone to respondent bias. Furthermore, the results derived from this research might be context-dependent and could be affected by organizational configurations, industry standards, and technology implementations; therefore, generalization of these results in finding the significance of blockchain-supported BI might be a challenge. Other research can be conducted to address the above-mentioned constraints by implementing longitudinal research where the impact of blockchain-supported BI and data transparency on SR might be explored. Furthermore, future research work can incorporate more mediating variables like the culture of the organization, the evolution of the digital world, and so on. In addition, it can concentrate on varying industries. This will incorporate more authenticity into the findings of the research work. This will show a deeper understanding of the strategic implications of the use of blockchain while referring to the field of business intelligence.

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The impact of logistics performance on economic growth: a comparative ARDL analysis for Türkiye and Poland

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Abstract: Transportation activities are among the most influential factors shaping economic growth and development. Since freight mobility and transport infrastructure play a strategic role in sustaining economic activity, understanding how different transport modes contribute to economic performance has become a critical research issue. This research aims to evaluate Poland, a significant economy in Central and Eastern Europe, and Türkiye, a bridge between Europe and Asia, and to reveal the role of transportation modes and supply chain integration in the development of economic growth in the Central and Eastern European region. The study employs the Autoregressive Distributed Lag (ARDL) modeling approach to capture both short-run and long-run relationships between transportation modes and economic growth, given that the variables exhibit different orders of integration. Annual time-series data covering the period 1995-2024 are used for both countries. The novelty of this research lies in its simultaneous, mode-specific comparison of Türkiye and Poland under a consistent methodology, providing new empirical evidence on the transport–growth nexus. Reveal that maritime transport contributes positively to long-term economic growth in Türkiye, while its effect in Poland is limited and negative. Rail transport emerges as the most influential and positively associated mode for economic growth in both countries. In contrast, air transport exhibits a negative and statistically significant effect only in Türkiye, whereas road transport shows no significant relationship in Türkiye but displays a short-term negative and subsequent positive effect in Poland. These results offer valuable insights for policymakers in designing efficient and sustainable transport strategies.

1 Introduction

Economic growth is one of the indicators that show how developed a country is. The reduction of trade barriers and the increased permeability of borders due to globalization have resulted in an increase in international trade, making the shipment of produced goods a strategic endeavor. Conceptually, logistics was previously considered only as a transport or shipping activity. Today, it encompasses various modes and directly contributes to economic development. Therefore, people now view logistics as the key to economic growth and competitiveness. Logistics has entered the business world's agenda in the 21st century in terms of developing capabilities in resource and organizational movements to achieve goals [1].

According to Ricardo, the expansion of foreign trade will not directly increase the quantity of value in a country; however, it will contribute very strongly to an increase in the quantity of goods and, consequently, in the total benefits derived [2], while Krugman emphasizes that trade gains are derived from efficient economies of scale in an integrated market [3]. The decrease in unit costs with increased production volume encourages trade and necessitates cross-border movement of goods. In this context, the efficient operation of logistics systems becomes a fundamental condition for benefiting from economies of scale. Reducing logistics infrastructure costs, shortening delivery times, and improving service quality positively affect both international trade volume and economic growth. However, rising actual costs of transportation are forcing companies to prioritize the utilization of vehicle capacity [4]. The main objective of this study is to comparatively examine the short-term and long-term effects of road, rail, sea, and air transportation on economic growth in Poland, a major economy in Central and Eastern Europe, and Türkiye, which occupies a strategic position between Europe and Asia. In this context, the study aims to contribute to the development of more effective and sustainable logistics and transportation strategies for policymakers by highlighting the different impacts of transportation modes on economic growth.

The logistics performance of countries is evaluated based on many different factors. The Logistics Performance Index (LPI), developed by the World Bank, is one such indicator. The LPI classifies countries according to sub-factors such as customs procedures, infrastructure quality, ease of international shipments, quality and adequacy of logistics services,

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traceability, and on-time delivery. The LPI was first published in 2007, with Türkiye ranking 34th. Its most recent ranking in 2023 was 38th.

Türkiye's geopolitical location confers logistical advantages. Türkiye's territories in Asia and Europe, along with its three coastlines and numerous neighboring countries, contribute to its advantages in various logistics modes. Located at the center of Europe–Asia–Middle East, Türkiye has the potential to become a regional logistics hub. In this regard, one of its most significant competitors among European countries is Poland. Poland is, after all, a European Union country and occupies a strategic position on the Trans-European Transport Network (TEN-T) corridors. According to LPI indicators, Poland rose from 40th place in 2007 to 28th place in 2023. This score indicates a considerable improvement in Poland's logistics performance, but Türkiye's declined. These indicators show that Poland has improved its integration with the European Union through the digitization of customs processes and infrastructure investments in rail and intermodal transport. These results offer practical insights for policymakers in designing efficient and sustainable transport strategies.

While there are numerous studies in the literature on logistics and logistics elements, supply chain management, logistics costs, modes of transport there is a need for more empirical and comparative studies that comprehensively evaluate logistics performance in relation to international trade and economic indicators, particularly for developing countries. This study aims to examine logistics performance indicators in the context of transportation modes and investigate the extent to which they affect countries' economic growth.

This study consists of five main sections. The first section is an introduction outlining the conceptual framework of the study, the second section is a literature review, the third section is the methodology, the fourth section is the analysis and results, and the final section is the discussion and conclusions. Microsoft Excel and EViews software were used in conducting this research.

2 Literature review

One of the key factors affecting economic growth is logistics activities. Various empirical studies reveal that improvements in logistics performance support both trade volume and economic growth [5,6]. Logistics performance is an significant factor that facilitates countries' integration into the global supply chain and increases their competitive power. Logistics cost advantage is linked to logistics performance [7], performing logistics operations on a small scale increases unit costs and leads to inefficiency [8]. With globalization, the improvement of logistics performance has become an indicator of countries' competitiveness. Therefore, logistics performance is an essential tool to monitor and develop, and it holds strategic importance in terms of international competition. The Logistics Performance Index, issued by the World Bank since 2007, has rendered countries' logistics performance a quantitatively comparable factor. The LPI evaluates countries in six dimensions: efficiency of customs procedures, quality of technical elements of transport and logistics, affordability of international shipments, quality and adequacy of logistics services, traceability of shipments, and timeliness of shipments [9,10]. Despite certain advances in the field of logistics, Türkiye lags behind its potential in the global rankings of LPI indicators [11,12].

Türkiye and Poland are two major competitors in the logistics sector. Different countries approach the evaluation of logistics performance from different perspectives. [13] investigated the impact of the logistics sector on economic growth in Türkiye, while [14] examined the impact of the export-led growth hypothesis on the Polish economy. Logistics performance indicators such as the LPI should be evaluated alongside macroeconomic and sectoral indicators. [15] emphasizes that liberalizing aviation, improving customs quality, and reducing corruption are each consistent with the proposition that they contribute to greater economic development. In general, logistics performance studies in the global and Turkish contexts are presented in Table 1 for worldwide logistics performance assessments and Table 2 for logistics performance assessments in Türkiye.

Table 1 Logistics performance assessment studies worldwide

Authors	Main Variables	Key Findings
[16]	GDP, infrastructure, LPI, international logistics	Türkiye and Poland can become significant logistics centers in Asia-Europe trade thanks to their strategic locations and development potentials.
[17]	Port service quality, system components, competitiveness, logistics processes	Quality port services and process management reduce transportation costs and increase competitiveness.
[18]	LPI, customs clearance, infrastructure, logistics qualification, tracking and monitoring	The LPI development of the two countries has diverged; this situation aims to explain the reasons for the changes in development.
[19]	Sustainable development, growth, indicators, innovation	There are differences in sustainability across EU regions. Local-level data access is significant for effective policy-making.
[20]	LPI, GCI, international transportation, tracking, timeliness	GCI has a significant impact on LPI. Improvements are needed in these areas for competitive strength.

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[21]	LPI, planning, quality control	The LPI may be insufficient. The Lithuanian example highlights the importance of information infrastructure and planning.
[22]	LPI, logistics performance indicators	LPI was used to compare the logistics performance of EU countries.

Table 2 Logistics performance evaluation studies in Türkiye

Authors	Main Variables	Key Findings
[11]	Logistics, quality, tracking, shipping, scheduling, infrastructure, customs clearance	Although Türkiye has made some progress, there has been no significant change in the global rankings; legal and technical improvements are recommended.
[13]	Transportation, storage, GDP	A unidirectional causal relationship has been found between economic growth and the logistics sector.
[14]	Export, foreign trade	The positive impact of exports on economic growth in Poland has been highlighted, and policy recommendations have been presented.
[23]	LPI, Liner Shipping Connectivity Index (LSCI), Enabling Trade Index (ETI), Availability and Quality of Transport Infrastructures (AQTI).	A country's integrated logistics performance is generally significantly, albeit to a limited extent, influenced by the logistics performance of neighboring countries.
[24]	Logistics, transport modes, geographical location	Logistics villages have been classified according to their geographical and infrastructure characteristics; a multi-criteria analysis has been proposed for the future.
[25]	Customs clearance, infrastructure, strategy	The strategic importance of logistics has been emphasized; the increasing importance of air transport has been mentioned.
[12]	Customs Clearance, LPI	Despite advancements in 2023, Türkiye continues to underperform in relation to its potential.

The impact of logistics performance on economic growth is a crucial subject that requires investigation on a country-specific level. Sea transport [26] rail transport [27], road [28] and air [29] freight transport indicators, along with infrastructure variables such as road length, allow for a more concrete measurement of countries' logistics capacities. Türkiye and Poland should be evaluated in terms of logistics performance indicators among European countries. These two countries can be considered as two European countries competing with each other in terms of international trade and logistics leadership. Türkiye stands out with its geopolitical position, which provides multimodal transport advantages from China and Asia to Europe, while Poland is an significant logistics transit country with TEN-T corridors. Therefore, the comparative analysis of Türkiye and Poland's logistics performance and the impacts of this performance on economic growth is an significant research topic in revealing logistics competition dynamics.

3 Methodology

3.1 Data set and model

In this study, annual time-series data covering the period 1995-2024 are employed for both countries. The time span is limited to approximately thirty years primarily due to data availability constraints, particularly for Poland. Economic growth is represented by Gross Domestic Product (GDP) measured in constant 2015 prices, which is used as the dependent variable. The independent variables representing logistics activity indicators include maritime freight transport measured in twenty-foot equivalent units (TEU) (DYT), rail freight transport measured in million ton-kilometers (DMT), road network length measured in kilometers (KYU), road freight transport measured in million ton-kilometers (KYT), and air freight transport measured in million ton-kilometers (HYT). The data were obtained from national statistical institutions, namely GUS [44] and Tuik [46], as well as from the World Bank databases [45]. To ensure data consistency and preserve the structural integrity of the econometric model, missing observations were completed using the linear interpolation method where necessary. Specifically, interpolation was applied to the following series: maritime cargo throughput for Türkiye (1995-1996); railway length in Poland (1995-1997); rail freight transport in Poland (2024); maritime cargo throughput in Poland (1996-1998); road freight transport in Poland (2024); and road network length in Poland (1995-1998 and 2024).

3.2 Econometric analysis

In econometric data analysis, the most important step in determining the research methodology is identifying the stationarity levels of the series. Accordingly, before proceeding to the empirical analysis, the KPSS test, developed by [30] to assess stationarity, was applied to determine the stationarity properties of the time series included in the dataset.

To examine the effects of logistics elements on economic growth in both countries, the ARDL (Autoregressive Distributed Lag) cointegration analysis was employed. This approach allows the use of series with different orders of integration within the same model, provided that the variables are integrated of order $I(0)$ or $I(1)$, while variables integrated of order $I(2)$ are not permitted. ARDL models combine the lagged values of the dependent variable and the lagged values of the independent variables within a single equation and can be applied to both $I(0)$ and $I(1)$ datasets. The selection of the appropriate ARDL model was based on the AIC and BIC information criteria. First, the ARDL models were estimated, and subsequently, long-run relationships were evaluated within the framework of the ECM (Error Correction Model). In this analysis, a negative and statistically significant ECT (Error Correction Term) indicates the existence of a long-run cointegration relationship. All analyses were conducted using the EViews software package.

3.2.1 KPSS stationarity analysis

The Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test, which is widely used to examine the stationarity properties of time series, was developed in 1992 by [30]. The most distinctive feature of this test is that its fundamental assumption regarding stationarity differs markedly from those of conventional tests—particularly the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests [31]. In the KPSS framework, the null hypothesis (H_0) is specified as *the series is stationary*. When the calculated test statistic exceeds the corresponding critical values, the null hypothesis is rejected, leading to the conclusion that the series is non-stationary [32]. Moreover, the KPSS test is reported to provide stronger performance in small samples ($n < 50$) compared to the ADF and PP tests [32,33].

3.2.2 Autoregressive Distributed Lag model and Error Correction model

One of the effective methods used to analyze cointegration relationships among different factors or variables is the Autoregressive Distributed Lag (ARDL) model. The ARDL approach was initially introduced by [34] and was later adapted to cointegration analysis through the development of the bounds testing approach by [35]. The ARDL model allows the simultaneous identification of both long-run and short-run relationships among variables. In studies examining cointegration, the ARDL framework enables the joint analysis of series with different orders of integration—specifically $I(0)$ and $I(1)$ within the same model. Moreover, the ARDL approach is recognized as a flexible and reliable method in small samples, as emphasized by [35,36]. Due to these properties, the ARDL model differs from traditional cointegration techniques such as those proposed by [37,38] and is generally considered to provide more efficient and robust results. Here, the selection of the appropriate model refers to determining the optimal lag length for each variable included in the analysis. For this purpose, the Akaike Information Criterion (AIC) and the Schwarz Information Criterion (SIC) are employed. Once the appropriate model is selected and the cointegration relationship is established, the long-run coefficients and the Error Correction Model (ECM) are estimated to calculate the rate at which short-run deviations converge to the long-run equilibrium [34,36]. The Error Correction Model (ECM) was initially developed by [37] in conjunction with the concept of cointegration. This approach aims to explain the dynamics of short-run fluctuations within the same analytical framework [37,38]. The formal expressions of these models are presented in Equations (1) and (2) [34-36].

$$Y_t = \alpha_0 + \sum_{i=1}^p \varphi_i Y_{t-i} + \sum_{j=1}^q \beta_{jl} X_{j,t-1} + \varepsilon_t \quad (1)$$

Y_t denotes the dependent variable, $X_{j,t}$ represents the independent variables, p and q_j indicate the lag lengths, and ε_t refers to the error term. This model has a dynamic structure that incorporates both the lagged values of the dependent variable and the lagged values of the explanatory variables.

$$\Delta Y_t = \alpha_0 + \sum_{i=1}^{p-1} \varphi_i * \Delta Y_{t-i} + \sum_{j=1}^q \sum_{l=0}^{q_j-1} \beta_{jl} * \Delta X_{j,t-1} + \lambda ECT_{t-1} + \varepsilon_t \quad (2)$$

In this equation, Δ denotes the first-difference operator (used to achieve stationarity), ECT_{t-1} represents the error correction term from the previous period (reflecting deviations from the long-run equilibrium), and λ denotes the error correction coefficient. A negative and statistically significant value of λ indicates that short-run disequilibria are corrected toward the long-run equilibrium.

4 Empirical findings

4.1 Empirical findings for Türkiye

According to the results of the KPSS stationarity analysis for the Türkiye datasets, some of the series are integrated of order $I(0)$, while others are $I(1)$. The results of the stationarity analysis are presented in Tables 3 and Table 4.

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Table 3 Stationarity test results at level for Türkiye

Variable	Test Statistic	Critical (1%)	Value (5%)	Critical (10%)	Value	Result(KPSS)
TlnGDP	0.7615	0.739	0.463	0.347		Not stationary
TlnDMU	0.8162	0.739	0.463	0.347		Not stationary
TlnDMT	0.8039	0.739	0.463	0.347		Not stationary
TlnDYT	0.8419	0.739	0.463	0.347		Not stationary
TlnKYT	0.5151	0.739	0.463	0.347		Stationary
TlnKYU	0.6842	0.739	0.463	0.347		Not stationary
TlnHYT	0.7161	0.739	0.463	0.347		Not stationary

Table 4 First-difference stationarity test results for Türkiye

Variable	Test Statistic	Critical (1%)	Value (5%)	Critical (10%)	Value	Result(KPSS)
ΔTlnGDP	0.1294	0.100	0.739	0.463	0.347	Stationary
ΔTlnDMU	0.3309	0.100	0.739	0.463	0.347	Stationary
ΔTlnDMT	0.1661	0.100	0.739	0.463	0.347	Stationary
ΔTlnDYT	0.4101	0.073	0.739	0.463	0.347	Stationary
ΔTlnKYT	0.4312	0.064	0.739	0.463	0.347	Stationary
ΔTlnKYU	0.0739	0.100	0.739	0.463	0.347	Stationary
ΔTlnHYT	0.1698	0.100	0.739	0.463	0.347	Stationary

Since the datasets are stationary at different levels and none of the series is integrated of order I(2), the ARDL approach was employed for the cointegration analysis. According to the AIC criterion, the appropriate ARDL specification was determined as ARDL(1, 1, 0, 0, 0). The model is presented in Equation (3), and the estimation results of this model are reported in Table 5.

$$TLNGDP = C(1) * TLNGDP(-1) + C(2) * TLNMT + C(3) * TLNMT(-1) + C(4) * TLNDYT + C(5) * TLNHYT + C(6) * TLNKYT + C(7) \quad (3)$$

Table 5 ARDL (1, 1, 0, 0, 0) model for Türkiye

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
TlnGDP(-1)	0.707*	0.116	6.087	0.000
TlnDMT	0.466	0.307	1.518	0.143
TlnDMT(-1)	-0.677*	0.258	-2.617	0.015
TlnDYT	0.744*	0.283	2.622	0.015
TlnHYT	-0.138*	0.042	-3.255	0.003
TlnKYT	0.049	0.0537	0.920	0.367
C	-4.099*	1.793	-2.285	0.032
R-squared	0.971	Durbin-Watson stat		2.117
Adjusted R-squared	0.963			
F-statistic	124.437			
Prob(F-statistic)	0.000			

(%1, ** %5, ***%10 significant) (R²: 0.963)

The results of the ARDL model indicate that economic growth in Türkiye is positively and statistically significantly influenced by its own lagged values. In addition, a positive and significant relationship is identified between economic growth and the one-period lag of rail freight transport, as well as air freight transport in its contemporaneous form. Another noteworthy finding is that the constant term in the model is negative and statistically significant. Detailed results for the long-run and short-run coefficients are reported in Table 6.

Table 6 Long-Run and Short-Run coefficients of the selected model

Long-Run Coefficients				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
TlnDMT	-0.712	0.894	-0.806	0.428
TlnDYT	2.543*	0.691	3.677	0.001
TlnHYT	-0.472**	0.214	-2.204	0.038
TlnKYT	0.169	0.203	0.830	0.419
C	-14.005***	7.923	-1.767	0.091

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Short-Run Coefficients				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
D (TlnDMT)	0.466**	0.205	-0.806	0.033
CointEq(-1)	-0.292*	0.050	-5.755	0.000
R-squared	0.515	Durbin-Watson stat		2.117
Adjusted R-squared	0.497			

(%1. ** %5. ***%10 significant). (F istatistik: 4.710*)

An examination of the long-run coefficients reveals that economic growth in Türkiye is positively and statistically significantly influenced by maritime freight transport, whereas air transport exerts a negative and statistically significant effect on growth. The results of the Error Correction Model (ECM) indicate that, in the short run, rail transport has a positive and statistically significant impact on economic growth. Moreover, the ECM coefficient, being negative and statistically significant in line with theoretical expectations, suggests that the system converges back to its long-run equilibrium at a speed of approximately 29%. The results of the diagnostic tests conducted to assess the reliability of the model indicate no evidence of autocorrelation, heteroskedasticity, or deviations from normality. These findings support the stability and validity of the estimated model (Table 7).

Table 7 Diagnostic test results

Test	Statistic	$\chi^2(p \text{ değeri})$	Result
Breusch–Godfrey LM	0.150	0.927	No autocorrelation.
Breusch-Pagan-Godfrey	11.180	0.083	No heteroskedasticity
Jarque–Bera	4.12	0.127	The series are normally distributed

Moreover, as illustrated by the CUSUM and CUSUMSQ curves presented below, the model remains within the 5% significance level confidence bounds, indicating that the ARDL model is stable (Figure1).

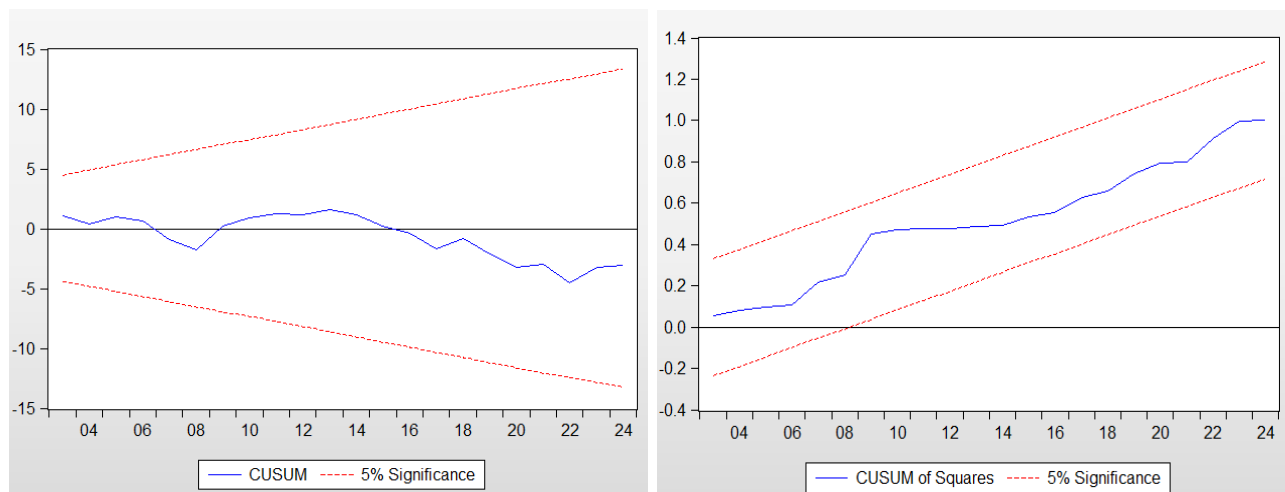


Figure 1 Cusum and Cusum² graphs for Türkiye

4.2 Empirical findings for Poland

According to the results of the KPSS stationarity analysis, none of the series for Poland is stationary at level, and most of the series become stationary after taking the first difference. The results of the stationarity analysis are presented in Tables 8 and 9.

Table 8 KPSS stationarity test results at level for Poland

Variable	Test Statistic	Critical Value (1%)	Critical Value (5%)	Critical Value (10%)	Result(KPSS)	Variable
PlnGDP	0.81	0.01	0.74	0.46	0.35	Not stationary
PlnDMT	0.20	0.10	0.74	0.46	0.35	Stationary
PlnDYT	0.80	0.01	0.74	0.46	0.35	Not stationary
PlnKYT	0.83	0.01	0.74	0.46	0.35	Not stationary
PlnKYU	0.83	0.01	0.74	0.46	0.35	Not stationary
PlnHYT	0.62	0.02	0.74	0.46	0.35	Not stationary

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Table 9 First-difference stationarity test results for Poland

Variable	Test Statistic	Critical Value (1%)	Critical Value (5%)	Critical Value (10%)	Result(KPSS)	Variable
ΔPlnGDP	0.11	0.10	0.74	0.46	0.35	Stationary
ΔPlnDMT	0.40	0.08	0.74	0.46	0.35	Stationary
ΔPlnDYT	0.35	0.10	0.74	0.46	0.35	Stationary
ΔPlnKYT	0.34	0.10	0.74	0.46	0.35	Stationary
ΔPlnKYU	0.11	0.10	0.74	0.46	0.35	Stationary
ΔPlnHYT	0.05	0.10	0.74	0.46	0.35	Stationary

Due to the fact that the series exhibit stationarity at different levels, the ARDL model was selected as the analytical method. Based on the AIC criterion, the most appropriate model for the Poland dataset was identified as ARDL(4, 0, 3, 2), and the corresponding model is presented in Equation (4). The estimation results of the selected model are reported in Table 10.

$$\begin{aligned} \text{PlnGDP} = & C(1) * \text{PlnGDP}(-1) + C(2) * \text{PlnGDP}(-2) + C(3) * \text{PlnGDP}(-3) + C(4) * \text{PlnGDP}(-4) + \\ & C(5) * \text{PlnDYT} + C(6) * \text{PlnDMT} + C(7) * \text{PlnDMT}(-1) + C(8) * \text{PlnDMT}(-2) + C(9) * \text{PlnDMT}(-3) + \\ & C(10) * \text{PlnKYT} + C(11) * \text{PlnKYT}(-1) + C(12) * \text{PlnKYT}(-2) + C(13) + C(14) * @TREND \end{aligned} \quad (4)$$

Table 10 Model ARDL (4,0,3,2) model for Poland

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
PlnGDP(-1)	0.436**	0.220	1.981	0.071
PlnGDP(-2)	0.489**	0.240	2.041	0.064
PlnGDP(-3)	0.210	0.224	0.940	0.316
PlnGDP(-4)	-0.634*	0.205	-3.090	0.009
PlnDYT	-0.430	0.256	-1.676	0.119
PlnDMT	1.082*	0.285	3.798	0.002
PlnDMT(-1)	0.151	0.278	0.545	0.595
PlnDMT(-2)	-0.291	0.243	-1.220	0.254
PlnDMT(-3)	-0.708**	0.325	-2.177	0.050
PlnKYT	-0.481***	0.259	-1.854	0.088
PlnKYT(-1)	1.000**	0.308	-3.240	0.007
PlnKYT(-2)	-0.407	0.286	-1.419	0.181
C	13.781**	6.019	2.295	0.041
@TREND	0.026	0.016	1.692	0.122
R-squared	0.994	Durbin-Watson stat		2.082
Adjusted R-squared	0.987			
F-statistic	153.437			
Prob(F-statistic)	0.000			

(%1. ** %5. ***%10 Significant) (R²: 0.987)

According to the results of the ARDL analysis, economic growth exhibits a relationship in the same direction with its past values; however, this effect is statistically significant and negative only at the fourth lag. In addition, a positive and statistically significant relationship is identified between economic growth and rail freight transport. Nevertheless, at the third lag of rail freight transport, the direction of the relationship turns negative. The road transport variable displays a positive effect in the contemporaneous period, while its lagged effect is negative. Another noteworthy finding is that the constant term is positive and statistically significant. Detailed results regarding the long-run and short-run coefficients (ECM model) are presented in Table 11.

Table 11 Long-Run and Short-Run coefficients of the selected model

Long-Run Coefficients				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
PlnDYT	-0.863***	0.417	-2.070	0.0607
PlnDMT	0.466	0.618	0.753	0.4655
PlnKYT	0.225	0.391	0.575	0.5755

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Short-Run Coefficients				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
C	13.788*	2.697	5.112	0.0003
@TREND	0.0263*	0.006	3.859	0.0023
D(PlnGDP(-1))	-0.065	0.135	-0.484	0.6374
D(PlnGDP(-2))	0.423*	0.138	3.063	0.0098
D(PlnGDP(-3))	0.633*	0.137	4.619	0.0006
D(PlnDMT)	1.081*	0.165	6.544	0.0000
D(PlnDMT(-1))	1.001*	0.200	4.994	0.0003
D(PlnDMT(-2))	0.709*	0.211	3.345	0.0058
D(PlnKYT)	-0.481**	0.184	-2.600	0.0233
D(PlnKYT(-1))	0.407**	0.155	2.608	0.0229
CointEq(-1)*	-0.498*	0.098	-5.060	0.0003
R-squared	0.515	Durbin-Watson stat		2.117
Adjusted R-squared	0.497			

(%1, ** %5, ***%10 Significant, F statistic: 5.119***)

According to the long-run coefficients, maritime freight transport has a statistically significant and negative effect on economic growth in Poland. The results of the Error Correction Model (ECM) indicate that economic growth is negatively related to its lagged value in the previous period; however, this relationship turns positive over time. In the short run, rail freight transport and its lagged values exert a statistically significant and positive impact on economic growth. In contrast, road freight transport has a negative and significant effect on economic growth in the short run, while the one-period lag of this variable reverses the direction of the effect to positive.

Moreover, the ECM coefficient being negative and statistically significant, in line with theoretical expectations, indicates that the model returns to its long-run equilibrium at an approximate speed of 50%. Diagnostic tests conducted to assess the reliability and stability of the model confirm that the core assumptions are satisfied. According to the test results reported in Table 12, no statistical problems such as autocorrelation, heteroskedasticity, or deviations from normality were detected. These findings support the validity and stability of the model.

Table 12 Diagnostic test results

Test	Statistic	$\chi^2(p \text{ değeri})$	Result
Breusch–Godfrey LM	2.162	0.335	No autocorrelation.
Breusch-Pagan-Godfrey	11.893	0.619	No heteroskedasticity
Jarque–Bera	0.719	0.620	The series are normally distributed

Moreover, as illustrated by the CUSUM and CUSUMS² curves presented below, the model remains within the confidence bounds at the 5% significance level, indicating that the ARDL model is stable.

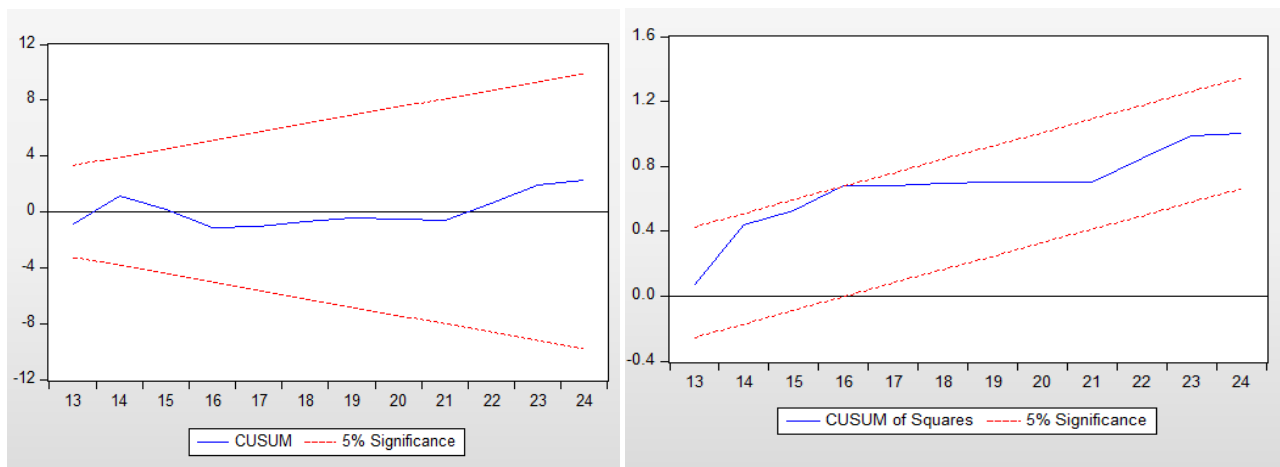


Figure 2 Cusum and Cusum² graph for Poland

5 Conclusions

The main aim of this study is to examine the impacts of logistics activities on the economic development of countries. In this context, the cointegration analysis method was used with time series data for Türkiye and Poland. To determine the cointegration method to be used, the stationarity levels of the data sets were analyzed using the KPSS test, and it was concluded that the series were stationary at different levels ($I(0)$ and $I(1)$). The ARDL cointegration analysis, which is suitable for series with such characteristics, was used. Accordingly, separate ARDL models were estimated for both countries, and short- and long-term dynamics were analyzed. The data sets used in the analysis consist of a 29-year time series covering the period 1995–2024 for both countries. The limitation in data length arose mainly due to the limited availability of statistical sources in Poland. Although the aim was to obtain a time series covering approximately 30 years, missing observations for some years were completed using linear interpolation.

This study aims to guide policymakers in strategic decisions for the logistics sector, rather than focusing on the current logistics capabilities of Türkiye and Poland. The comparative analysis of these two countries highlights the increasing competition in their logistics sectors. Poland stands out in the European logistics network in many different ways. The Baltic–Adriatic and North–South corridors, which are part of the Trans-European Transport Network (TEN-T) project, pass through Poland, providing a strategic advantage. In addition, European Union funds, customs facilities, and free movement opportunities also strengthen Poland's hand in this sector. In 2007, Türkiye ranked 34th and Poland 40th in the LPI ranking, but by 2023, Türkiye had fallen to 38th place while Poland had risen to 26th place. On the other hand, Türkiye is located on the mandatory transit route for Asia–Europe trade due to its geopolitical position. It stands out with its strategic role on the Trans-Caspian International Transport Corridor (Middle Corridor), strong maritime infrastructure, and vast domestic market potential.

The results obtained from the ARDL models created for both countries differ according to transport modes. The results can be summarized as follows based on variables:

- Both countries' own lagged values influence economic growth. In Türkiye, growth shows a positive and significant correlation with its one-period lagged value. This shows that the growth process exhibits strong continuity and inertial structure. For Poland, economic growth was found to be unidirectional and significant in the first, second, and fourth periods and counter-directional and significant in the fourth period. This indicates that despite short-term fluctuations, the economy tends towards equilibrium in the long term, and cyclical shocks subside over time.
- In Türkiye, maritime transport has a positive and significant impact on economic growth in the long term. In Poland, however, this correlation was found to be negative and significant. In Türkiye, the study shows that port infrastructure, which supports foreign trade volume, contributes to growth. In Poland, however, it states that maritime transport does not hinder growth; rather, due to the country's geographical location and limited port capacity, it makes an indirect and relatively weak contribution to growth.
- The correlation between rail transport and economic growth in Türkiye was found to be positive in the short and long term but inversely related with a one-period lag. In Poland, rail transport is positive and significant in the short term but insignificant in the long term. In Türkiye, high infrastructure costs and capacity constraints limit growth in the short term but increases in production and foreign trade mean that railways contribute positively to growth in the long term. In Poland, railway investments, particularly through EU funds and the TEN-T corridors, are effective in the short term, but their contribution to long-term growth remains limited. These results are consistent with other research findings [39–41].
- The negative and statistically significant long-term impact of air transport on economic growth in Türkiye indicates that limited cargo carrying capacity and high cost structure restrict its contribution to growth. In Poland, however, no strong relationship was found between air transport and economic growth, suggesting that the divergence from previous studies may be largely due to methodological differences [42,43].
- In Türkiye, no significant correlation was found between road transport and economic growth in the short or long term. The saturation of road transport, rising environmental costs, and high oil prices can explain this result (Santos, 2018). However, Poland found a negative and significant correlation in the short term, and a positive and significant correlation with a lag period. This data indicates that investment costs suppressed growth in the initial period but subsequently contributed to growth through increased production.
- The fact that the error correction coefficients are negative and statistically significant for both countries indicates that the models strongly revert to long-term equilibrium [35,37,38]. The following period eliminates approximately 49% of deviations in Türkiye and 29% in Poland. The positive trend coefficient found to be significant in the Polish model indicates that changes in the demographic structure and production transformations support economic growth [40,41].

Overall, the findings offer actionable insights for policymakers and logistics stakeholders in Central and Eastern Europe by highlighting the importance of multimodal transport strategies in enhancing and the results show that economic

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growth in Türkiye is positively correlated with maritime transport, while in Poland it is negatively correlated; in both countries, rail transport plays a decisive role in economic development. Türkiye's strategic position on maritime transport and the Middle Corridor, as well as Poland's strong infrastructure in the EU logistics network, shape the logistics dynamics of the two countries in different directions. Road transport stands out as a complementary factor in Türkiye and a delayed and cyclical one in Poland. supply chain integration and resilience under increasing geopolitical and economic uncertainty. Future research should expand the scope of data sets, conduct detailed analyses at the regional level, and diversify modeling approaches. With improved data quality, it will be possible to obtain more robust econometric estimates.

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Integration of electric freight logistics and energy communities: a system - level operating model

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Keywords: electric vehicle, logistics, freight transport, renewable energy, energy community.

Abstract: The electrification of road freight transport is a priority objective of European decarbonisation policy; however, its large-scale implementation remains constrained by charging infrastructure availability, electricity grid capacity limits, and the specific energy demand profiles of freight transport operations. From a logistics perspective, this transition requires coordinated management of material, information, and energy flows within increasingly complex transport systems. The aim of this research is to examine how electric freight vehicles can be integrated into future logistics networks through operating models based on energy community principles. The study is grounded in a systematic review of relevant literature published between 2020 and 2025, focusing on technological trends, electric road freight vehicles, and energy supply configurations. The analysis indicates that existing research predominantly addresses route optimisation, infrastructure development, and capacity management, while system-level cooperation between energy communities and electric freight transport remains underexplored. The study proposes a conceptual model based on replaceable high-capacity energy storage units and decentralised charging infrastructure, enabling improved coordination between transport flows and energy flows. The framework supports more efficient utilisation of renewable energy and enhanced economic and network performance and is positioned relative to prevailing logistics and operational paradigms.

1 Introduction

Electrification of the transport sector is widely recognised as a key instrument of European decarbonisation policy. In the context of road freight logistics, however, electrification does not represent a simple technological substitution, but a structural transformation affecting transport operations, infrastructure planning, and supply chain coordination. The transition introduces additional constraints related to charging time, battery capacity, and grid integration, which directly influence transport flow management and network performance.

Recent studies [1] and [2] underline the increasing charging demand of heavy-duty vehicles and the resulting pressure on electricity distribution networks. At the same time, advances in energy storage integration and vehicle-to-grid (V2G) applications [3-5] suggest that electric freight vehicles may play a broader role within decentralised energy systems. Despite these developments, current research remains largely centred on route optimisation and charging infrastructure placement, with limited attention given to the integrated coordination of logistics networks and energy community structures.

Against this background, the present study develops a system-level perspective that connects freight transport operations with decentralised energy community frameworks.

2 Systematic literature review on logistics energy system integration

To ensure a comprehensive and methodologically rigorous examination of the topic, a systematic literature review (SLR) methodology was applied (Figure 1).

1. Description of motivation: The aim of the current research is to explore new opportunities for a two-way cooperation model between energy communities and electric vehicles after analysing the relevant literature on the electrification of road transport vehicles.

2. Formulation of research questions: The research aimed to answer the following questions:

- What are the development trends in the operation of electric road transport vehicles?
- What are the current operating models for electric road freight transport?

3. Defining keywords and their combinations: In order to answer the specific questions, publications were identified in the Scopus database using the following keywords: electric vehicle, logistics, freight transport, renewable energy, energy community.

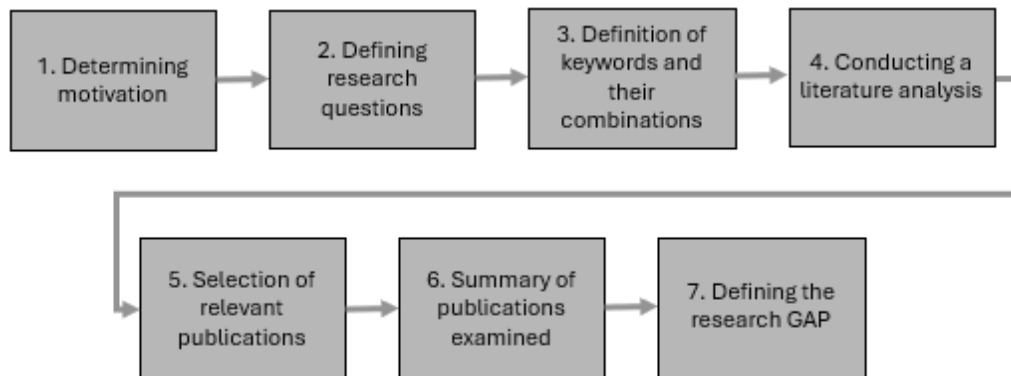


Figure 1 Steps of the systematic literature review [self-edited]

The following search string was used, which identified 223 documents:

(electromobility OR "electric vehicle*" OR "electric freight" OR e-mobility) AND (logistics OR freight OR "urban logistics" OR "transport system*") AND ("energy community" OR "local energy community" OR "renewable energy community" OR "energy sharing" OR "microgrid" OR "smart grid" OR "vehicle-to-grid" OR "V2G" OR "distributed energy resource*" OR "DER integration")

In order to focus on the most relevant publications, the number of articles was narrowed down as shown in Figure 2:

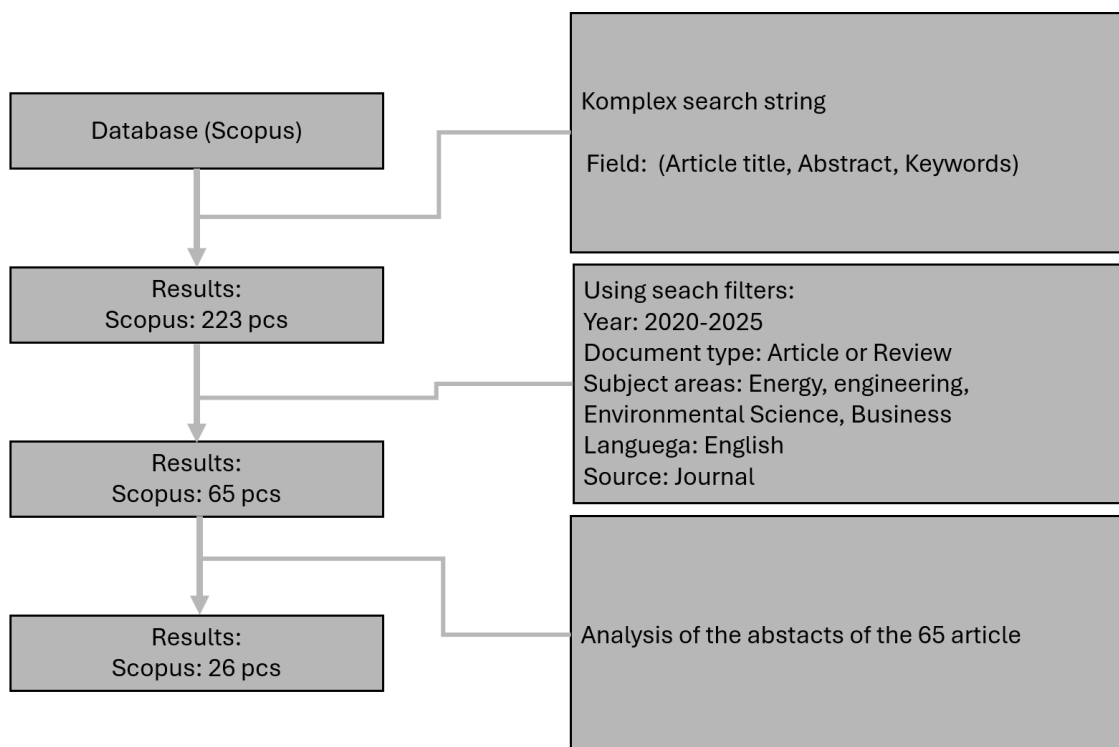


Figure 2 Process of literature analysis [self-edited]

4. Conducting a Literature Analysis

Based on the complexity of the search string, the filters applied, and a preliminary review of the titles of the results, the resulting sample of 65 publications was considered sufficient for in-depth thematic analysis, so no further narrowing was applied.

5. Selection of relevant publications

Abstract-level screening revealed that numerous studies deal with fleet-level electromobility and logistics vehicles in terms of urban freight transport, road transport, and last-mile delivery. The sample was subsequently narrowed down to 26 relevant studies focusing specifically on road freight transport, alternative energy production, energy communities, and the research questions formulated in Section 2.

6. Summary of publications examined

Current research and development trends:

In order to review current research trends in electric road freight transport, a detailed analysis of the relevant literature was conducted. The aim of the analysis was to identify which vehicle categories, technological solutions and operating concepts are currently the focus of scientific research. Table 1 summarises the key development trends, with a particular focus on vehicle technology, charging infrastructure optimisation and solutions for integrating electric freight transport into the energy system.

Table 1 Research and development trends [self-edited]

Areas under investigation	Main findings/direction	Application context	Related references
Main vehicle categories	Dominance of electric trucks and light commercial vehicles	Urban and long-distance freight transport	[1,2,4,9,21-23]
Infrastructure development direction	Optimisation of charging infrastructure location and sizing	Depot charging, public charging network	[10,15,16]
Digital and optimisation tools	Smart charging stations, IoT-based data collection, MILP models	Fleet management, energy demand forecasting	[24,25]
Location optimisation of charging points	Reducing network losses and increasing security of supply	Electricity distribution networks	[6,7]
Vehicle technology trends	Comparison of BEV and FCEV systems	Short- and long-distance freight transport	[2,28]
Energy system integration	Application of V2G technology	Reducing peak grid loads, cost optimisation	[3-5,11,27,28]
Sustainability and operational performance in road freight	Link between environmental sustainability and logistics operational efficiency	Road freight sector	[29,30]

Current models of electric road freight transport

Scientific work on electrified road transport focuses mainly on optimising traditional transport, route planning, and charging habits. Early studies on smart grids primarily interpreted electric vehicles as controllable loads within the energy system, focusing on demand management rather than their potential role as active elements of decentralized energy systems [8]. Some of the research is based on integrated logistics-energy models that examine the joint optimization of heavy goods vehicle fleets, charging infrastructure, and distributed energy generation (DER) at the regional or terminal level [9,10]. While advanced charging control strategies, such as priority-based or fuzzy logic approaches, improve the performance of local networks, they are typically implemented at the level of individual vehicles or stations and do not take into account coordination mechanisms within the energy community [11]. Several studies analyse the integration of photovoltaic power generation and fast charging infrastructures based on demand and energy forecasts; however, these solutions are typically based on stationary storage concepts and fixed charging locations [12]. Another group of publications presents fleet operation and charging management models, where the focus is on route planning [13] and the coordination of depot and public charging [14-16]. These approaches aim to implement an electrified version of traditional freight transport logic. Table 2 contains only studies that present specific electric freight transport operating models and are directly related to fleet operation, charging decisions, route planning, or freight transport logistics costs. General energy system, smart city, or autonomous transport models have been deliberately excluded.

Table 2 Current models of road freight transport [self-edited]

Model type	Focus / operating logic	Ref.
Integrated logistics–energy model	Heavy goods vehicle fleet, micro-network, DER, TCO-based optimisation	[9]
Terminal-level integrated model	Joint planning of fleet, charging infrastructure and energy storage	[10]
Fleet-level energy management	Operation of EV fleet as an aggregated energy storage system	[14]
Fleet operation model	Coordination of depot and public charging	[15]
Route and charging scheduling model	Optimisation of logistics costs and energy requirements	[16]

In general, the analysis indicates that the aim of the models examined is to achieve the smallest possible deviation from traditional transport, as illustrated in Figure 3, taking into account the charging limitations of the vehicles.

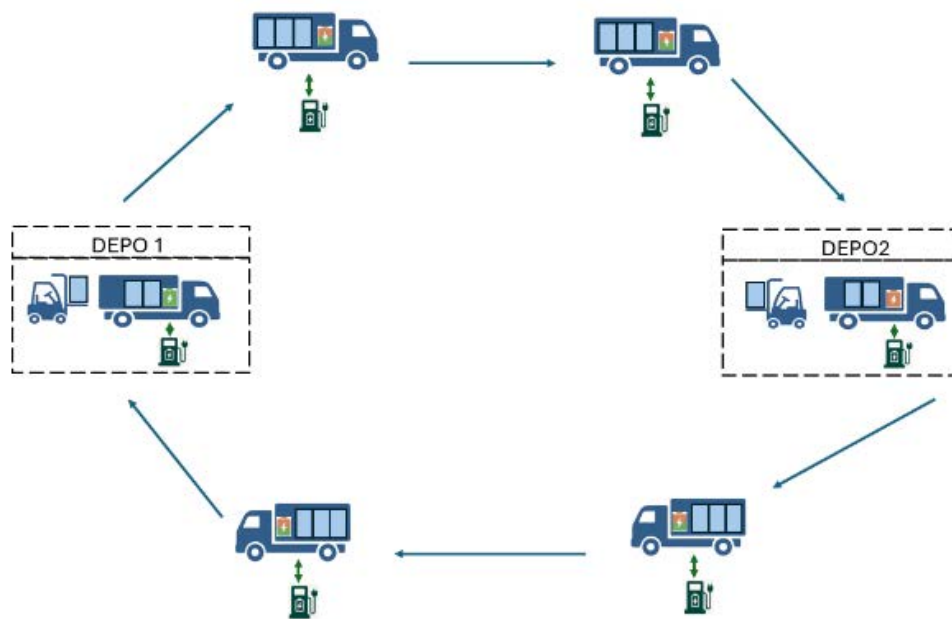


Figure 3 Traditional model [self-edited]

A common feature of the operational models presented is that they interpret electric road freight transport as an electrified version of traditional transport logic. In all cases, the main objective is to achieve the smallest possible deviation from traditional freight transport operations, even with the range and charging limitations of the vehicles. Industrial pilot projects and strategic partnerships between logistics service providers and vehicle manufacturers demonstrate the growing interest in electrified long-distance freight transport, although these initiatives are still largely based on traditional charging paradigms [17]. Integrated logistics-energy models examine the operation of heavy goods vehicle fleets, charging infrastructure and distributed energy resources (DER) at regional or terminal level within a common optimisation framework.

In the case of terminal-level integrated models, logistics hubs – such as distribution centres or depots – become the central units of analysis. These approaches jointly plan fleet size, the number and location of charging points, and energy storage capacities. Here, too, the operating logic is strongly linked to depot-based freight transport, where vehicles are charged at specific locations and time slots.

Fleet-level energy management models treat electric vehicle batteries as aggregated energy storage devices and focus primarily on reducing energy costs and optimising network charges. Although this approach is closer to integration with the energy system, vehicles are still treated as units with fixed energy storage.

Fleet operation and route and charging scheduling models are most directly related to daily freight transport practices. Their aim is to coordinate routes, charging times and charging locations in order to minimise logistics costs and energy consumption. The models typically operate in deterministic or limited stochastic environments and treat electric vehicles as functional equivalents of conventional fleets.

Similar challenges in system-level coordination were also found in other areas of transport, for example in maritime logistics, where a joint optimization of logistics planning and energy management is required to ensure operational flexibility [18].

Overall, the analysis indicates that most operational models conceptualise electric road freight transport primarily as an adaptation of conventional logistics structures, in which the characteristics of electric propulsion must be adapted to existing logistics structures. Although some approaches already apply an integrated logistics-energy perspective, system-level concepts integrating mobile, replaceable energy storage within energy community frameworks remain insufficiently developed.

7. Defining research gap in logistics–energy system coordination

Although numerous studies analyse the coordination of electric transport systems and decentralised energy resources within smart city environments, limited attention has been given to the specific logistics requirements of road freight transport and the integrated management of material and energy flows in supply chain networks [19]. Existing research primarily interprets electrification as an adaptation of conventional logistics processes, treating electric vehicles as energy-constrained transport units with fixed storage capacity. Consequently, the potential role of swappable energy storage systems and the system-level integration of freight transport into energy community frameworks remain insufficiently explored.

This gap is particularly relevant from a logistics perspective, where the coordination of transport flows, energy flows, and infrastructure capacity determines operational efficiency and network stability. The scientific novelty of this study lies in proposing a system-level operating model that repositions electric freight transport as an active, mobile energy storage component within decentralised energy communities.

3 Results - presentation of the new model

Based on the identified research gap, a system-level redesign of the charging concept is proposed for energy storage devices in road vehicles. The operational efficiency of a community aimed at optimising electrified road transport is based on the functional selection of participants. These actors are located at different points in the energy production, distribution, consumption and services chain. However, they can also perform multiple functions within the energy community. Transport companies, for example, can also be participants in the system through the production, use and transport of energy via their vehicle batteries. Production companies represent the customer side of the logistics chain, but at the same time they are also potential producers and consumers of energy. Electricity suppliers provide the basis for the stable operation of the system, but the management of energy produced by local energy producers in a constantly changing manner is a challenge for them.

The hierarchical structure of the model:

1. Energy producers (PV systems)
2. Energy suppliers
3. Transport companies, consumers and mobile energy storage facilities
4. Manufacturing companies
5. Coordinating integrator (central BMS server operator)

High penetration of distributed PV systems introduces significant balancing challenges for electricity suppliers due to the network load caused by production peaks. A new energy community model (Figure 4) offers an effective solution for capturing and redistributing surplus energy over time without overloading the grid. By operating transport vehicles with replaceable energy storage devices, it enables the creation of a circular logistics process with the following objectives:

1. Replacing the storage units of vehicles arriving at the depot or loading area (battery swap)
2. Transporting depleted storage units to a charging point
3. Charging of storage units
4. Transporting the charged storage units to the battery swap area
5. Loading the vehicle in parallel with or after the storage swap.
6. Continuous execution of the operational cycle

The operation of the system is coordinated by an organisation that acts as a coordinator and integrator, operating the central BMS (Battery Management System) server and responsible for optimising energy and information flows, scheduling charging and replacement processes, and settling accounts between the market participants involved.

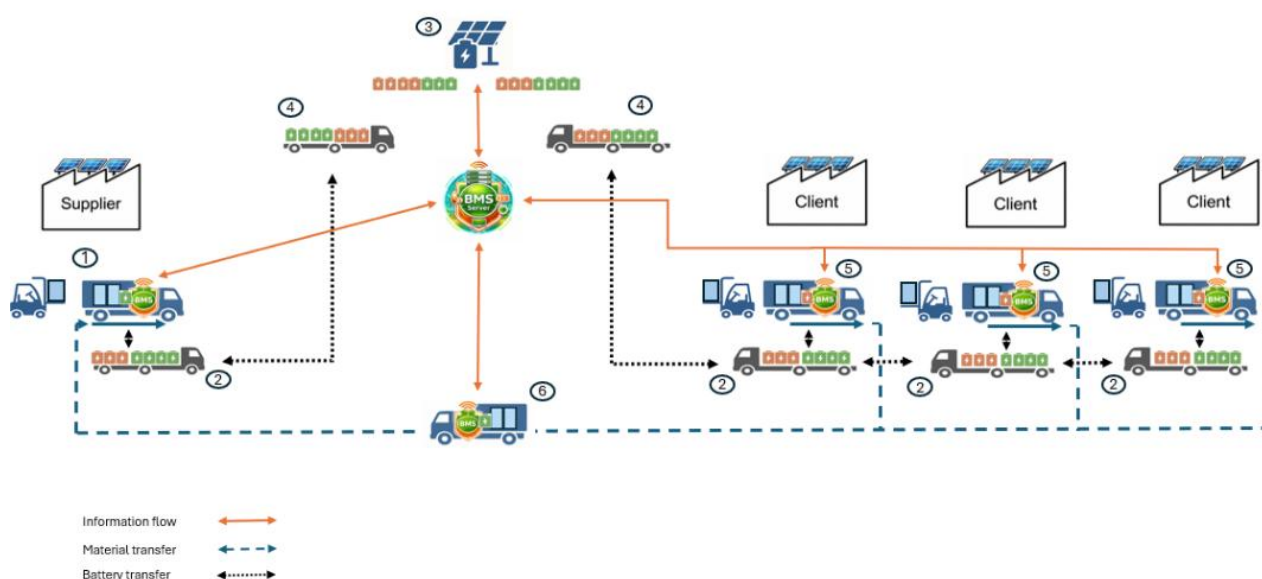


Figure 4 New model [self-edited]

Integration of electric freight logistics and energy communities: a system - level operating model

László Seres, Péter Tamás

There are several approaches to settlement within energy communities, but the organised spot market structure applied by HUPX is particularly compatible with the proposed operational framework (Figure 5). HUPX's day-ahead and intraday markets provide transparent, market-based reference prices that are suitable as a basis for energy allocation and settlement within the energy community. The system is based on a battery swap logistics cycle, which is controlled by the central BMS server using a charging strategy aligned with HUPX spot market prices. Charging and replacement processes are optimised at 15-minute intervals, taking into account day-ahead and intraday market prices and available solar production. Settlement within the energy community is linked to the HUPX reference, supplemented by operational and flexibility components, ensuring transparent and auditable cost sharing and supporting operational cost allocation within freight logistics networks. Interchangeable energy storage devices provide physical flexibility, reducing the risks associated with balance group deviations while contributing to the smoothing of network loads.

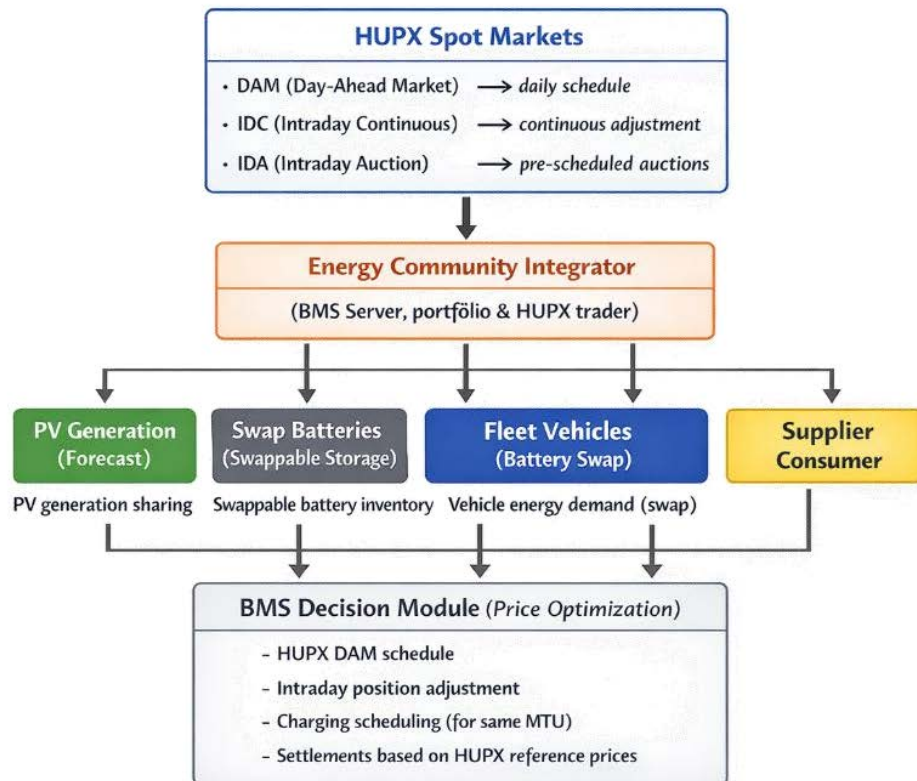


Figure 5 HUPX-based energy community optimisation framework [self-edited]

The model's operation is consistent with the data reporting and market compliance requirements of organised electricity markets, ensuring the system's long-term scalability and market integration. Table 3 shows a comparison between the proposed system model and the traditional operating model.

Table 3 Comparison of operating approaches [self-edited]

Aspects	Traditional approach	Energy community-based approach
Conceptual approach	Preserves traditional freight transport logic with minimal deviation using electric propulsion	System-level redesign integrating transport and energy systems within an energy community
Role of the vehicle	Primarily an energy consumer with a fixed onboard battery	Energy consumer and mobile energy storage unit
Energy storage type	Fixed, non-swappable battery	Swappable battery (battery swapping concept)
Charging concept	Direct vehicle charging at fixed or high-power charging stations	Decoupled charging of batteries optimised in time and location
Renewable energy integration	Limited and mostly indirect	Direct and active integration within the energy community

Handling of PV peak production	Not addressed at system level	Excess energy absorbed and temporarily shifted via storage
V2G applicability	Limited, vehicle-level implementation	System-level, business-oriented V2G integration

The comparison highlights that while the traditional approach essentially preserves the classic transport logic and treats electric propulsion primarily as an alternative energy source, the energy community-based model implements a system-level redesign that integrates transport and energy subsystems within an integrated system framework. For transport companies, the model offers significant cost-cutting opportunities, such as reduced transport and maintenance costs and the use of V2G technology, which allows the battery capacity of transport vehicles to become a source of revenue in the free-market energy trade. For manufacturing companies, it offers reduced logistics costs and increased energy stability, which provides a competitive advantage in the market. For electricity suppliers, decentralised energy storage reduces the peak effects of PV systems, enabling network development cost reductions and optimal scheduling. For renewable energy producers, it ensures stable returns and business stability. Overall, energy efficiency increases across the entire energy community, system-level instability decreases, and positive economic effects are expected, such as a reduction in import energy demand.

4 Discussion

The proposed framework suggests that electric road freight transport should be interpreted not merely as an electrified extension of conventional logistics systems, but as an integrated element of decentralised energy communities embedded within supply chain networks. By positioning electric freight vehicles as mobile energy storage units, the model expands the prevailing research perspective, which has predominantly focused on route optimisation, charging infrastructure placement, and fleet-level energy management.

The spatial and temporal decoupling of battery charging from vehicle operation introduces additional flexibility into transport flow management and supports improved coordination between material flows and energy flows. Such system-level integration is particularly relevant in logistics environments characterised by infrastructure constraints and high penetration of renewable energy sources. The incorporation of organised electricity market mechanisms, including HUPX pricing structures, further connects logistics decision-making with market-based energy signals, strengthening the economic feasibility of coordinated logistics–energy operation.

These findings indicate that enhanced synchronisation of transport operations and decentralised energy management may represent a decisive factor in the long-term development of electric freight logistics.

5 Conclusion

The electrification of road freight transport has become a key area of research in sustainable logistics in recent years. Based on the literature review, current scientific approaches primarily focus on the electrification of traditional logistics operations, with particular emphasis on route optimisation, charging infrastructure placement, and vehicle fleet energy management, while less attention is paid to the integrated coordination of logistics and energy systems. In response to this shortcoming, this study presents a model that interprets electric freight vehicles as active, mobile energy storage elements of energy communities. The use of replaceable, high-capacity energy storage devices allows the charging process to be separated spatially and temporally from vehicle operation, reducing downtime and facilitating the more efficient integration of renewable energy sources. From a logistics perspective, this approach supports improved coordination of material flows and energy flows within transport networks. The energy community-based model offers a solution to logistical, energy and economic challenges at the same time: decentralised energy storage reduces peak grid loads, enhances system stability, and creates additional business opportunities through V2G-based services. The findings indicate that the future development of electric freight transport depends increasingly on the systemic integration of logistics operations and decentralised energy management. Future research should prioritise quantitative modelling, simulation-based validation, and pilot-scale implementation studies, in order to identify the economic and operational conditions required for broader application.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process: During the preparation of this manuscript, the author used ChatGPT (OpenAI) to improve language clarity and stylistic quality. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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A fuzzy-based framework for evaluating cruise ports of call

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Keywords: cruise, port of call, port selection factors, fuzzy AHP.

Abstract: The cruise industry plays a pivotal role in the development of the tourism sector of nations. Yet, policies to attract cruise liners to call at a cruise terminal are still questionable. To fill literature gaps, the purpose of the study is to discuss the selection of cruise carriers (CCs) at ports of call. Based on relevant research and the operating features of cruise ships, the port selection factors (PSFs) that CC consider for port calls are firstly explored. A demand gap model based on a fuzzy Analytic Hierarchical Process (AHP) is then proposed to evaluate perceived differences on PSFs between port companies (PCs) and CCs. Finally, for a practical application, the PMP Exploitation Joint Stock Company (PMC) and its customers (i.e., CCs) in the BRVT port were surveyed to validate the model. The result shows that “port travel features” and “port management” concern CCs the most. Furthermore, currently, the BRVT port is facing two significant gaps, including: “health and sanitation conditions of the local population” (positive gap) and “existence of modern tourist centers” (negative gap). This study may provide useful information for port authorities to suggest practical policies in developing its cruise businesses. Besides, the sample size is a research limitation; thus, future research should extend the number of respondents for better policies.

1 Introduction

The cruise industry has proliferated worldwide at the beginning of 20th century [1]. Initially, it was very popular in North America and a part of Europe and dramatically shifted to Asian countries in the last few decades [2-4]. As a result, global tourism revenue, including the contribution from the tourism industry in Asian areas, grew comparatively rapidly at the end of the 2000s. This also led to rapid growth of the global cruise industry.

Along with the quick growth of the cruise sector, the income of cruise lines and ports also surged aftermath [5]. Consequently, port cities and/or nearby tourist attractions have experienced a significant economic impact. It is noteworthy that there are two types of ports: the “homeport” and the “port of call”. The former refers to the port that is the starting, or ending, point for a cruise, or even both these points [6-8]. The latter is used in reference to any port where a cruise stops for a short time when it is visiting several places [4,9,10]. These types of ports generate revenues for cruise liners and port companies.

Undoubtedly, port operations are highly complex, especially at the port of call. Such a process may enable the development of port to attract tourist ships. It has been argued that enhancing cruise port operations is essential for cruise carriers to select ports of call. Martínez Moya and Feo Valero [11] found that environmental and cultural treasures of the port, such as facilities, accessibility, security, infrastructure, and provisioning (local supply of foods, drinks, and freshwater), port charges (dockage fees, etc.) are main factors for the port of call. Kodzi and Saeed [12] postulated the importance of critical factors, such as port connectivity, tourism infrastructure, safety, security, city travel services, and public transportation networks for the port of call from the cruise's perspective. Nonetheless, to the best of the authors' knowledge, no single previous study has assessed the PSFs from the port companies' point of view.

The vast majority of past studies, when assessing crucial PSFs, often base on unilateral perspectives of port stakeholders, such as cruise liners [13], travel agencies [14], or cruise brokers [15]. So, proposed solutions did not reflect the requirements of port companies, which are also an imperative port stakeholder. It could be said that the determination of the demand gap, which is defined as the discrepancy between cruise liners and port companies in terms of PSFs, is necessary to appeal to more cruise carriers in the context of severe competition in the cruise industry. Yet the determination of the demand gap in previous research is rarely addressed. It can be argued that the demand gap guides port companies to re-allocate scarce resources optimally. Thanks to that, port operations might be improved to maximize cruise carriers' requirements, thereby encouraging them to elect an appropriate port to call.

Moreover, in practice, the determination of critical PSFs for the port of call is basically MCDM (multiple criteria decision-making) problem [5,16,17]. The fuzzy AHP (Analytic Hierarchy Process) is arguably the most popular method applied to solve multifaced issues, especially under the ambiguous, uncertain judgment environment [18]. Its major

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advantage is to address many complex decision-making problems with a simple computational procedure. Accordingly, the application of fuzzy AHP might be the theoretical contribution for MCDM research.

The purpose of the study is to assess the selection of ports of calls for cruise carriers. Unlike prior studies, this article surveyed the cruise carriers in the PM Vietnam Cruise Port (PMP) and the PMP Exploitation Joint Stock Company (PMC) as an empirical study. From the relevant literature and cruise ship operations, the current article first investigated PSFs that cruise carriers consider when electing a port to call. Next, the fuzzy AHP method was adopted to estimate PSFs' weights from the viewpoint of CCs and PCs. Finally, a demand gap model (DGM) was proposed to assess the perceived difference on PSFs between CCs and PCs. From that, PCs can make managerial policies to boost their ports' operations, and attract more CCs.

The structure of the paper is as follows: Sections 2 and 3 examine PSFs in the cruise industry and the research methodology, respectively. Section 4 then presents research findings. Lastly, we offer conclusions, acknowledge the study's limitations, and propose directions for future research.

2 Literature reviews

It has been argued that most prior literature pays most attention to factors of port selection based on the demand of cruise liners, passengers and travel agents [7,12,19]. In the early phase of the cruise-service development, some studies were performed to identify critical factors impacting the port of call. For example, Demirel and Yucenur [20] found that there are two groups of PSFs, including cruise terminal facilities and local characteristics. More specifically, the former comprises berthing facilities, port fees, maritime rescue systems, oil water supply facilities, passenger service centres, cruise terminal concession policy, and political stability. Meanwhile, the latter embraces the natural environment at ports, important historical sites, cultural and natural attractions, and convenient transportation. Among these, traffic at the cruise port, the local natural environment, and government policies are illustrated to have the largest effect size on the port of call. On the other hand, competition among cruise ports tends to focus on understanding the services offered by the port to cruise liners and passengers, as well as comprehending the life cycle of travelers at the port of call and the marketing strategies employed. According to Brida, et al. [3], there are 8 key factors considered when selecting the port of call from the cruise ship associations' viewpoint. They are natural and cultural assets, port facilities, the distance between the home port or the departure port and the next port, port security, port infrastructure, material supply replenishment, port expenses, and market sales.

Some research on cruise tourism in East Asia stressed the significance of PSFs, for instance, 24-hours tourism service centres, logistic services, special government units, as well as planning and development resources to attract CCs for a port of call. According to Wang, et al. [21], the port transportation is concerned by CCs to select a port of call. Several studies also suggest that the traffic congestion problem at cruise ports can be overcome by multimodal transportation and improving infrastructure to develop cruise tourism. It is widely admitted that this solution might help PCs avoid unnecessary competition with some larger ports outside the region in attracting international cruise operators.

Past studies also accentuated the importance of physical appearance and cultural qualities of the port location in selecting the port of call from the cruise liners' viewpoint [22,23]. Besides, Sanz-Blas, et al. [10] posited that reputation, and awareness of the cruise port are very effective and important factors for the cruise passenger to visit a port. Thus, these two factors are argued to have influence the port of call. Tseng and Yip [24] studied about the Magong port development of international cruise tourism with the help of the Taiwan Port Corporation. By surveying the Taiwan cruise companies, shipping agencies and travel agencies, they found that the local government should center on local cultural activities, natural landscape, and the transport connectivity to attract cruise carriers. Moreover, James, et al. [25] argued that the development of berthing facilities, the cost of the cruise terminal, and the effect of the weather positively impact the selection of CCs for a port of call. On top of that, some features of CPs (i.e., port infrastructure, services for cruise passengers, and the political and regulatory framework) impact CCs' decisions.

Lekakou, et al. [8] also postulated that the fruitful partnership between cruise companies and ports is an essential factor for cruise liners in selecting a port of call. It is explained that such a relationship helps improve port marketing communications and the local economy. Besides, a sufficient source market, the berthing wharf, and dedicated facilities are noticed by cruise carriers [26]. Other studies also argued that incentive schemes provided by port governments are crucial factors for CCs in calling a port [2]. Thus, these factors are asserted to affect the competitiveness of cruise ports. Kodzi and Saeed [12] demonstrated that service provided from the waterside area and landside area, and service quality are the basic requirements that CCs demand for the port of call. From the result, it can be confirmed that port of call quality may play a vital role in meeting customer satisfaction, and in turn, affecting their intention to revisit port cities.

According to the above literature review, it has been argued that most previous literature on PFSs has taken a unilateral perspective, focusing on cruise operators, travel agents, and passengers. Hence, this paper fills this literature gap by evaluating PSFs for the port of call from the viewpoint of CCs and PCs.

3 Research method

3.1 Research framework

The purpose of this research is to assess PSFs of cruise carriers. In doing so, the research framework is shown in Figure 1. This research first bases on the characteristics of the cruise operating and related literature to create PSFs for cruise carriers. Secondly, a fuzzy AHP is then adopted to weight the PSFs from the viewpoint of CCs and PCs. Next, the DMG based on those weights is established. Improved policies are ultimately proposed to enhance port companies' operations and attract more cruise carriers.

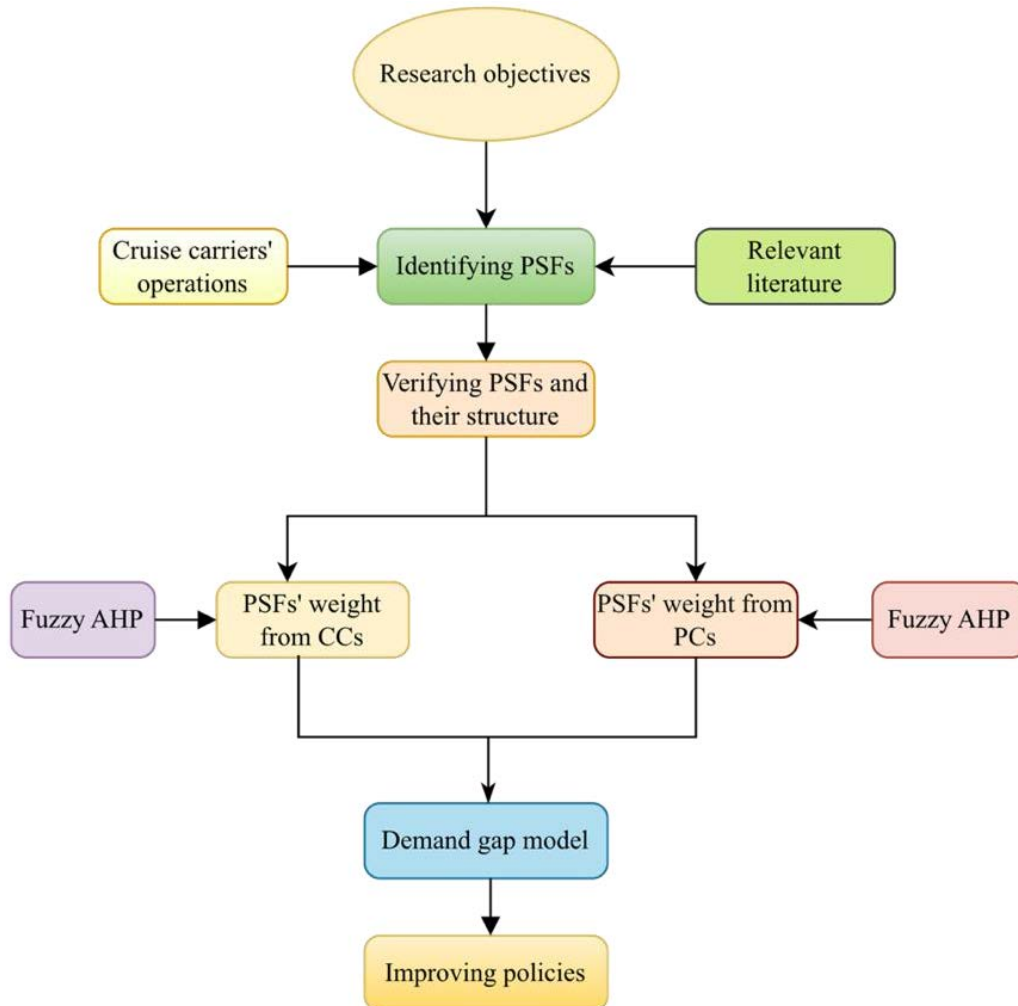


Figure 1 Research framework

3.2 Establishment of cruise port selection factors

From the operational features of CCs and the relevant literature, sixteen PSFs are generated, as follows:

(1) Port environment:

The port's geographical location is a critical criterion for attracting cruise carriers as a port of call. In addition, the local city image, which is represented by the culture, food, languages, historical, and attractive places, is argued to be an imperative element for cruise carriers to select the port of call. Also, political factors are crucial for selecting the port of call.

(2) Port inland transportation:

For the large cruise market, the convenience of port traffic is crucial. Tourists use convenient transportation to travel to cultural sites and downtown for sightseeing. They also spend time in metropolitan areas before and after sailing.

(3) Port travel features:

The overall attractiveness of the cruise port is likewise reflected by the adequacy of tourist interest and landmarks. Additionally, different cruise ports, and different shore excursions are chiefly dependent on historical, geographical, social, and cultural aspects.

(4) Port operations management:

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For cruise operators, a sound policy, such as reasonable taxes and port fees, can attract them to berth. Further, visa-free provision, the convenience of customs, immigration control and quarantine (CIQ), and the rescue system are the main factors impacting the port of call.

Thanks to such definitions, the paper created a hierarchical structure for PSFs. Moreover, five practical industrial panels from CCs and PCs were invited to revise PSFs to ensure that they were understandable for the official interview. Moreover, the interdependencies among PSFs were verified. As a result, the official hierarchy structure of cruise PSFs is seen in Table 1, including four constructs and 16 PSFs.

Table 1 The hierarchy structure of cruise PSFs

Layer1: Constructs	Layer 2: Cruise PSFs		Sources
Port environment (PE)	PE1	Port location	[7,12]
	PE2	Health and sanitation conditions of the local population	[15,25]
	PE3	Reputation and image of the local city	[14,19]
	PE4	Political stability	[6,24]
Port inland transportation (PT)	PT1	Port accessibility	[2,4]
	PT2	Availability of inland transport systems	[2,23]
	PT3	Proximity international airports	[3,20]
	PT4	Frequency of flights and planning of flight routes	[12,21]
Port travel features (PF)	PF1	Variety of land-based tourism opportunities	[4,23]
	PF2	Availability of local historic landmarks	[2,19]
	PF3	Existence of modern tourist centers	[14,19]
	PF4	Hosting of large-scale local entertainment events	[4,6]
Port operations management (PM)	PM1	Visa-free access for cruise passengers	[4,6,19]
	PM2	Efficiency of customs, immigration control, and quarantine procedures (CIQ)	[2,19]
	PM3	Incentive programs for cruise ships to dock at the port	[6,24]
	PM4	Specifications for maritime rescue systems	[2,4]

3.3 Data collection

Because of using the fuzzy AHP method to estimate PSFs' weights, a pair-wise comparison questionnaire developed by Saaty and Tavana [27] was drafted to capture the perception on PSFs from the perspectives of CCs and PCs. Based on Table 1, we developed a survey questionnaire comprising four constructs and 16 PSFs.

Based on the assistance from the VNCC port government, the paper elected six cruise liners with experienced cruise businesses (i.e., Royal Caribbean International, Princess Cruise, Holland America Lines, Celebrity Cruise, Norwegian Cruise Lines, Carnival Cruise Lines) to answer the CCs' expert questionnaires. Meanwhile, 10 senior employees from PMC were singled out to fill out the PCs' expert questionnaires. As a result, we had 24 respondents in total. Further, for verifying the validation and reliability of the surveys, responses were tested by the Consistency Index (CI) and Consistency Ratio (CR), as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (1)$$

and:

$$CR = \frac{CI}{RI} \quad (2)$$

Where: $\lambda_{\max}$ is the maximum eigenvalue for individual pairwise comparison matrixes (IPCMs) while n is the number of elements in IPCMs. Besides, RI is a randomized index shown in Table 2 [27]. In practice, it is suggested that the $CR \leq 0.1$ is an acceptable range. In this paper, the software package "eigen ()" in RStudio was first used to find $\lambda_{\max}$.

Then CI and CR were obtained by Equations (1) and (2). Consequently, several samples' CI or CR were greater than 0.1, thus corresponding respondents were asked again to revise their responses until the CI and CR tests were fitted.

Table 2 The randomized index (RI) for the consistency test

<i>n</i>	3	4	5	6	7	8	9	10	11	12
RI	0.58	0.882	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

The profiles of the sample, shown in Table 3, demonstrate that all respondents from CCs and PCs have at least five years of working experience in the cruise business. Besides, over half of the subjects have managerial positions (8/17 for CCs and 8/11 for PCs). Note, the high level of qualifications of the respondents endorses the reliability of the survey.

Table 3 The profile of respondents in the VNCC case

Features	Range	CCs		PCs	
		Frequency	%	Frequency	%
Age	30-40	4	23.53	3	27.27
	41-50	7	41.18	6	54.55
	Over 50	6	35.29	2	18.18
Education	Professional high school	4	23.53	1	9.09
	Bachelor	8	47.06	7	63.64
	Master or above	5	29.41	3	27.27
Seniority	5~10	6	35.29	2	18.18
	11~16	7	41.18	6	54.55
	Over 16	4	23.53	3	27.27
Job title	Senior staff	9	52.94	5	45.45
	Manager	5	29.41	4	36.36
	President/General Director	3	17.65	2	18.18

3.4 The weights of the PSFs

To estimate the weight of the PSFs, this paper surveyed 17 respondents from CCs and 11 from PCs. To explain how to use fuzzy AHP, this paper deployed the PE constructs (including PE1, PE2, PE3, and PE4) from CCs' responses. Note that there are 17 responses from CCs.

3.4.1 Combination of fuzzy positive reciprocal matrix (FPRM)

Assume that the matrix $\tilde{A}$ is a combined fuzzy matrix with n criteria (i.e., PSFs) as (3):

$$\tilde{A} = [\tilde{a}_{ij}]_{n \times n} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} \quad (3)$$

Where: element $\tilde{a}_{ij}$ is triangular fuzzy numbers (TFNs) with parameters:

$$\tilde{a}_{ij} = \begin{cases} [l_{ij}, m_{ij}, u_{ij}], & \text{if } i > j \\ [1, 1, 1], & \text{if } i = j \\ [\frac{1}{u_{ji}}, \frac{1}{m_{ji}}, \frac{1}{l_{ji}}], & \text{if } i < j \end{cases}.$$

From m respondents in the sample data, then we have m individual matrixes. Such m matrixes can be combined to generate the fuzzy matrix $\tilde{A}$ with elements $\tilde{a}_{ij}$ as:

$$\tilde{a}_{ij} = [l_{ij}, m_{ij}, u_{ij}] = \left[\min_{1 \leq k \leq m} \{a_{ij}^{(k)}\}, \left(\prod_{k=1}^m a_{ij}^{(k)} \right)^{1/m}, \max_{1 \leq k \leq m} \{a_{ij}^{(k)}\} \right] \quad (4)$$

$$i = 1, 2, \dots, n, \quad j = 1, 2, \dots, n \text{ and } k = 1, 2, \dots, m.$$

For the sample data of the PE construct, we obtained 17 matrices. Thanks to Equation (4), the FPRM (termed $\tilde{A}'$) can be formed as:

$$\tilde{A}' = \begin{bmatrix} [1.000, 1.000, 1.000] & [0.111, 0.182, 4.000] & [0.333, 0.362, 0.500] & [0.143, 0.333, 0.500] \\ [0.250, 5.499, 9.000] & [1.000, 1.000, 1.000] & [0.250, 0.255, 0.500] & [0.333, 0.345, 1.000] \\ [2.000, 2.765, 6.000] & [2.000, 3.927, 4.000] & [1.000, 1.000, 1.000] & [0.500, 0.708, 1.748] \\ [2.000, 3.007, 7.000] & [1.000, 2.897, 3.000] & [0.572, 1.413, 2.000] & [1.000, 1.000, 1.000] \end{bmatrix}$$

3.4.2 Crisp positive reciprocal matrix (CPRM)

The present paper uses geometric mean to defuzzify the $\tilde{A} = [\tilde{a}_{ij}]_{n \times n}$ into CPRM $A = [a_{ij}]_{n \times n}$. In doing so, the fuzzy element $\tilde{a}_{ij} = [l_{ij}, m_{ij}, u_{ij}]$ in $\tilde{A}$ is defuzzified adopting the formula:

$$a_{ij} = \sqrt[4]{l_{ij} \cdot 2m_{ij} \cdot u_{ij}}, \quad i = 1, 2, \dots, n, \quad j = 1, 2, \dots, n \quad (5)$$

Revert to the example, Equation (5) is used to defuzzify the matrix $\tilde{A}'$:

$$A' = \begin{bmatrix} 1.0000 & 0.3482 & 0.3843 & 0.2981 \\ 2.8720 & 1.0000 & 0.3001 & 0.4464 \\ 2.6025 & 3.3328 & 1.0000 & 0.8134 \\ 3.3543 & 2.2400 & 1.2294 & 1.0000 \end{bmatrix}$$

3.4.3 The PSFs' weights

According to Saaty and Tavana [27], the weights of criteria (i.e., PSFs) is estimated from the eigenvector of matrix $A = [a_{ij}]_{n \times n}$. Let $W = [w_1, w_2, \dots, w_n]$ be the weights of criteria (i.e., PSFs). Then, the vector W is found by (6):

$$\begin{cases} AW = \lambda W \\ \sum_{i=1}^n w_i = 1, \quad i = 1, 2, \dots, n. \end{cases} \quad (6)$$

Besides, thanks to the feature of reciprocity of the matrix A , Saaty and Tavana [27] proposed NGMR (Normalization of the Geometric Mean of the Rows) to compute W . Accordingly, the $W = [w_1, w_2, \dots, w_n]^T$ is obtained by the normalized geometric means of a_{ij} in matrix A as:

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$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} \left(\prod_{j=1}^n a_{1j} \right)^{1/n} / \sum_{i=1}^n \left(\prod_{j=1}^n a_{ij} \right)^{1/n} \\ \left(\prod_{j=1}^n a_{2j} \right)^{1/n} / \sum_{i=1}^n \left(\prod_{j=1}^n a_{ij} \right)^{1/n} \\ \vdots \\ \left(\prod_{j=1}^n a_{nj} \right)^{1/n} / \sum_{i=1}^n \left(\prod_{j=1}^n a_{ij} \right)^{1/n} \end{bmatrix}, i = 1, 2, \dots, n. j = 1, 2, \dots, n. \quad (7)$$

Back to the example, the weight of matrix A^1 is found by Equation (7):

$$W = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \begin{bmatrix} 0.4469 / 4.6076 \\ 0.7876 / 4.6076 \\ 1.6296 / 4.6076 \\ 1.7433 / 4.6076 \end{bmatrix} = \begin{bmatrix} 0.0970 \\ 0.1709 \\ 0.3537 \\ 0.3784 \end{bmatrix}$$

By the same way, the local weights of the remaining PSFs are computed and exhibited in the fourth field of Table 4 (for CCs) and Table 5 (for PCs).

Table 4 The final weights of PSF's for CCs

Layer 1: Constructs	Global weights (%)	Layer 2: PSFs	Local weights (%)	Global weights (%)
PE	21.88	PE1	9.70	2.12
		PE2	17.09	3.74
		PE3	35.37	7.74
		PE4	37.84	8.28
PT	23.26	PT1	24.3984	5.68
		PT2	30.024	6.98
		PT3	24.8472	5.78
		PT4	20.7304	4.82
PF	28.99	PF1	30.4365	8.82
		PF2	29.1924	8.46
		PF3	19.6527	5.70
		PF4	20.7184	6.01
PM	25.87	PM1	30.47	7.88
		PM2	29.32	7.59
		PM3	18.56	4.80
		PM4	21.65	5.60

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Table 5 The final weights of PSF's for PCs

Layer 1: Constructs	Global weights (%)	Layer 2: PSFs	Local weights (%)	Global weights (%)
PE	26.99	PE1	17.07	4.61
		PE2	27.26	7.36
		PE3	34.31	9.26
		PE4	21.36	5.77
PT	23.08	PT1	27.62	6.38
		PT2	26.42	6.10
		PT3	26.41	6.09
		PT4	19.55	4.51
PF	21.96	PF1	31.61	6.94
		PF2	32.02	7.03
		PF3	14.04	3.08
		PF4	22.34	4.90
PM	27.97	PM1	31.68	8.86
		PM2	33.44	9.35
		PM3	18.04	5.05
		PM4	16.83	4.71

3.4.4 Consistency test

We substitute Equation (7) into Equation (6). As a result:

$$\lambda I = (AW)W^{-1} \quad (8)$$

Where $\lambda I \approx (\lambda_1, \lambda_2, \dots, \lambda_n)$. Aftermaths, the maximum eigenvalue of matrix A ($\lambda_{\max}$) is approximated by averaging the $(\lambda_1, \lambda_2, \dots, \lambda_n)$ as:

$$\lambda_{\max} \approx \frac{1}{n} \cdot \sum_i^n (\lambda_1 + \lambda_2 + \dots + \lambda_n) \quad (9)$$

For the matrix A' , from Equations (8) and (9), $\lambda_{\max}$ is attained:

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix} = \left(\begin{bmatrix} 1.0000 & 0.3482 & 0.3843 & 0.2981 \\ 2.8720 & 1.0000 & 0.3001 & 0.4464 \\ 2.6025 & 3.3328 & 1.0000 & 0.8134 \\ 3.3543 & 2.2400 & 1.2294 & 1.0000 \end{bmatrix} \times \begin{bmatrix} 0.0970 \\ 0.1709 \\ 0.3537 \\ 0.3784 \end{bmatrix} \right) \times \begin{bmatrix} 0.0970 \\ 0.1709 \\ 0.3537 \\ 0.3784 \end{bmatrix}^{-1} = \begin{bmatrix} 4.1779 \\ 4.2388 \\ 4.1942 \\ 4.0211 \end{bmatrix}$$

$$\Rightarrow \lambda_{\max} \approx 4.2388$$

With the $\lambda_{\max}$ of 4.2823 found by Equation (9), the consistency of matrix A' is tested by CI and CR, as seen in Equations (1) and (2). Consequently, $CI = 0.0796$ and $CR = 0.0903$ ($< 10\%$) illustrate the consistency for judgments. Likewise, the remaining judgment in the VNCC case can be tested and shown in Table 6. Arguably, they are all consistent.

Table 6 The results of the consistency test for the sample data in the VNCC case

Respondents	Layers	$\lambda_{\max}$	RI	CI	CR
Cruise carriers	Layer 1	4.1593	0.882	0.0531	0.0602
	Layer 2: PE	4.2388	0.882	0.0796	0.0903
	Layer 2: PT	4.1146	0.882	0.0382	0.0433

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Respondents	Layers	$\lambda_{\max}$	RI	CI	CR
Port companies	Layer 2: PF	4.2135	0.882	0.0712	0.0807
	Layer 2: PM	4.2167	0.882	0.0722	0.0819
	Layer 1	4.2569	0.882	0.0856	0.0971
	Layer 2: PE	4.2586	0.882	0.0862	0.0977
	Layer 2: PT	4.2536	0.882	0.0845	0.0959
	Layer 2: PF	4.1917	0.882	0.0639	0.0725
	Layer 2: PM	4.1682	0.882	0.0561	0.0636

3.4.5 Global weight of PSFs

The PSFs' global weights in Layer 2 can be obtained by multiplying the local weight by their correlated construct weights in Layer 1. The results of PSFs' final weights for CCs are shown in the last field of Table 4. The results indicate that the CCs' respondents are most concerned with the construct of PF (28.99%), followed by PM (28.87%), PT (23.26%), and PE (21.88%). Further, in Layer 2, the CCs' respondents pay much attention to PF1(8.82%), PF2 (8.46%), and PE4 (8.28%).

Furthermore, based on the above steps 3.4.1~3.4.5, the PSFs' final weights for PCs' importance measures are found and shown in the last field of Table 5. The results indicate that the PCs' respondents are most concerned with the construct of PM (27.97%), followed by PE (26.99%), PT (23.08%), and PF (21.96%). Further, in Layer 2, the PCs' respondents pay more attention to PM2 (9.35%), PE3 (9.26%), and PM1 (8.86%) and PE2 (7.36%).

3.4.6 Demand gap analysis

To attract port calls from cruisers, port companies (PCs) need to meet the demand of cruiser carriers (CCs). In the current paper, DMG is developed to measure the differences of the perceived demands between PCs and CCs. From that, PC managers can make police lessen the gap. The fundamental concept of the DMG is that a PSF with a higher CCs' expected weight (called a CC weight) and a lower PCs' expected weight (called a PC weight) will be a higher demand gap with higher priorities for improving. In this paper, a PSF with the CC weight > the PC weight is defined as a "negative gap", meaning the PC managers should put in more effort to improve this PSF. On the contrary, a PSF with the CC weight < the PC weight is defined as a "negative gap", implying this PSF could be overinvested. Thence, scarce resources allocated to it should be employed elsewhere. Further, a PSF with the CC weight = the PC weight is defined as the "no gap". Obviously, the policy for PSF should "keep working with no changes".

According to the collected data, a two-dimensional matrix was constructed to evaluate the demand gap of PSFs. Then, the matrix is divided into two zones by the identity line (the 45-degree line). More specifically, PSFs in Zone I mean weights from PCs are greater than ones from CCs. Thence, they are evaluated as "positive gaps". By contrast, PSFs in Zone II indicate that weights from CCs are greater than ones from PCs. Therefore, they are assessed as "negative gaps."

For the empirical case of the VNCC, PSFs' demand gap indices are presented in the final column of Table 7, while their positions are displayed in Figure 3. Evidently, there are seven positive demand gaps in Zone I. Among which, the demand gap indexes for PE2, PM2, and PEE are managerially significant while the remaining ones are insignificant. Therefore, PMC managers should focus on improving high-gap PSFs, especially PE2. On the contrary, Quadrant II also has 7 positive gap PSFs. More specifically, the largest positive-gap PSFs include PF3 (-2.26), PE4 (-2.51), PF1 (-1.88), and PF2 (-1.43). It is noteworthy that the resources committed to PF3 should be re-allocated elsewhere. Broadly speaking, port managers had better transfer resources from PSFs in Quadrant II to ones in Quadrant I to improve port's operational capacities.

Furthermore, a gap value was introduced to evaluate the size of the demand gap. It was initiated by measuring the distance between a PSF's position to the 45-degree line, as mentioned in Figure 3. For instance, the coordinate of point PE2 is (7.36%, 3.74%); as a result, its demand gap is positive (3.62%), representing the distance between the point and the 45° lines. In the same way, PF3's demand gap has a negative value of -2.26%.

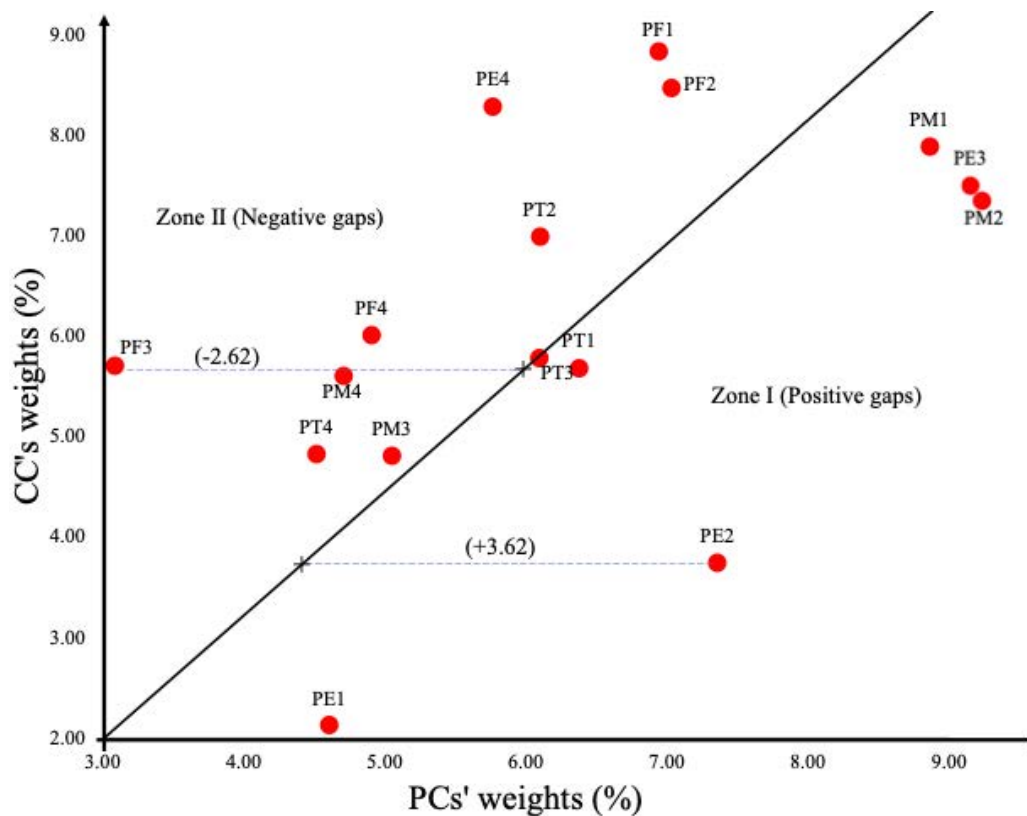
Table 7 The DGM of cruise PSFs

PSFs	PCs (%)	CCs (%)	Zone	DGM (%)
PE1	4.61	2.12	Zone I (Negative gaps)	+2.48
PE2	7.36	3.74		+3.62
PE3	9.26	7.74		+1.52
PT1	6.38	5.68		+0.70
PM1	8.86	7.88		+0.98
PM2	9.35	7.59		+1.77
PT3	6.09	5.78		+0.32
PF1	6.94	8.82		-1.88

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PSFs	PCs (%)	CCs (%)	Zone	DGM (%)
PF2	7.03	8.46	Zone II (Negative gaps)	-1.43
PF3	3.08	5.70		-2.62
PF4	4.90	6.01		-1.10
PM3	5.05	4.80		0.25
PT2	6.10	6.98		-0.89
PM4	4.71	5.60		-0.89
PT4	4.51	4.82		-0.31
PE4	5.77	8.28		-2.51



4 Results and discussions

4.1 The PSF's weight for the cruise company

Table 4 demonstrates that in Layer 1, the highest-weight PSFs are PF (port travel features) and PM (port management). And in Layer 2, PSFs receive more attention from CCs, including PF1, PF2, and PE4. Put succinctly, “variety of land-based tourism opportunities”, “availability of local historic landmarks”, and “political stability” play a crucial role in the port of call from CCs' perspective.

Prior studies also emphasized the land-based tourism opportunities in developing cruise tourism. For instance, Kodzi and Saeed [12] argued that a cruise port offering multiple types of experiences (i.e., cultural sites, shopping, nature, adventure, gastronomy, and relaxation) can satisfy first-time visitors and repeat cruisers. Moreover, it is widely admitted that for many cruise passengers, especially first-time visitors [7], history and heritage [15] are key motivations for going ashore. On top of that, political stability is essential for a cruise port of call. It is explained that political stability ensures passenger safety [25], operational reliability [14], positive destination image [6], and long-term viability within cruise itineraries [24]. In summary, from a practical perspective, these findings provide PCs with an actionable checklist of what CCs value most; thus, investment and marketing strategies can be prioritized accordingly. On top of that, these findings provide a decision framework and performance indicators for PCs to redesign services to attract cruise liners.

4.2 The demand gap

Results in Table 7 indicate that PE2 (health and sanitation conditions of the local population) is the most significant positive gap criterion (+3.62). This indicates that this criterion is highly important to cruise stakeholders, while its current

performance is perceived as weak. This implies that PMC executives may be underestimating or overlooking the role of local health and sanitation conditions in shaping the overall city image. From a cruise tourism perspective, passengers are highly sensitive to hygiene [4], cleanliness [2], and public health conditions [3]. Hence, poor sanitation or visible health issues can negatively affect the destination's image, even if port facilities themselves are adequate. From practical views, this finding gives PCs a basis for prioritizing investments to enhance health and sanitation conditions at terminal areas. If they do so, they can improve performance to cruise stakeholders and reduce perceived operational risk.

As shown in Table 6, PF3 (existence of modern tourist centers) has the most significant negative gap (-2.26), indicating that this PSF is over-invested. In practice, the modern tourist center, including 24-hour services, transportation, and visa-free services, encourages cruise companies to select the port of call [9]. However, in the context of the VNCC case, resources for PF3 should be employed elsewhere to improve the port's operations.

5 Conclusions

The main purpose of this paper is to examine the demand gap in PSFs between the CCs and PCs. First, based on relevant literature and CCs' features, a total of 16 PSFs for cruise operators were established and classified into 4 dimensions, namely "port environment", "port inland transportation", "port travel features", and "port operations management". Secondly, this study uses the fuzzy AHP method to determine the PSFs' weight. From that, the port company can formulate appropriate policies to develop the port and attract more cruise carriers. The empirical results indicate that two significant gaps are "health and sanitation conditions of the local population" (the positive gap), and "existence of modern tourist centers" (the negative gap). Based on empirical results, practical policies to attract CCs for the PMC were proposed.

To validate this model, we used 11 PCs and 17 CCs, as provided in the paper, for a survey. To improve the validity of the questionnaire, this study conducted interviews with experts to find the answers to the surveys. However, for more accurate empirical results, more samples are needed for further research. Furthermore, this paper uses the fuzzy AHP method to determine the weights of PSFs to improve the validity of data collected from experts. In principle, the fuzzy AHP method might enhance data verification in decision-making scenarios. Besides, the sample size is a research limitation. This study only surveys 17 CCs and 11 PCs. Future research should increase the number of respondents to inform better policies.

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From sensor data to supply chain decisions: a mechanism framework for IIoT and sensor networks in automotive supply chains

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From sensor data to supply chain decisions: a mechanism framework for IIoT and sensor networks in automotive supply chains**Monika Zatrochová**

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Keywords: industrial internet of things, sensor networks, automotive supply chain, digital twins.

Abstract: Automotive logistics and supply chain networks coordinate complex multi-tier material flows under strict sequencing, transport synchronization, and quality constraints. These systems are highly sensitive to information-flow latency, exception-handling delays, and disruptions affecting inbound, production, and distribution logistics processes. Although Industrial Internet of Things (IIoT) and sensor-network technologies enable real-time visibility across material and transport flows, prior literature frequently emphasizes technological capability rather than clearly operationalized logistics decision mechanisms. This study develops a decision-centric mechanism framework explaining how IIoT-enabled sensing is translated into governed logistics decisions influencing reliability, responsiveness, inventory–production synchronization, and disruption mitigation in automotive supply chains. Based on a structured 2025 literature review (Scopus, Web of Science, IEEE Xplore; $n = 13$ included studies), four recurring sensor-to-decision mechanisms are identified: (M1) real-time visibility and traceability control, (M2) predictive asset and quality logistics, (M3) inventory–production flow synchronization, and (M4) event-driven logistics decision support. The contribution lies in formalizing reproducible sensor-to-decision pathways that connect sensing capability, analytics, decision triggers, and execution routines to measurable logistics performance outcomes.

1 Introduction

Automotive logistics networks coordinate thousands of components across multi-tier supply chains while ensuring synchronized material flows, production sequencing, and transport reliability. Late information, inaccurate inventory records, and poorly governed exception handling destabilize inbound logistics, production logistics, and outbound distribution processes.

Despite extensive deployment of Industrial Internet of Things (IIoT) and sensor technologies (e.g., RFID, telematics, condition sensors), value realization in logistics remains uneven (Figure 1). Many initiatives increase visibility of material and information flows but do not explicitly define how sensor signals are operationalized into governed logistics decisions such as call-off adjustments, rerouting, quality containment, or dynamic allocation.

Research gap: Existing literature frequently treats visibility as a performance outcome rather than specifying the operational mechanism linking sensing capability to logistics decision routines. The “sensor-to-decision” chain is often under-specified.

Aim of the study: The aim of this paper is to develop a structured mechanism framework that links IIoT sensing capabilities to reproducible logistics decision mechanisms in automotive supply chains.

Research question: How are IIoT-enabled sensor signals translated into governed logistics decision routines that measurably influence material-flow reliability, responsiveness, and resilience?

Contribution: The study advances a decision-centric lens by distinguishing sensing capability, operational mechanism, decision trigger, and logistics performance impact. The proposed framework structures four recurring mechanisms (M1–M4) and identifies enabling conditions required for scalable implementation.

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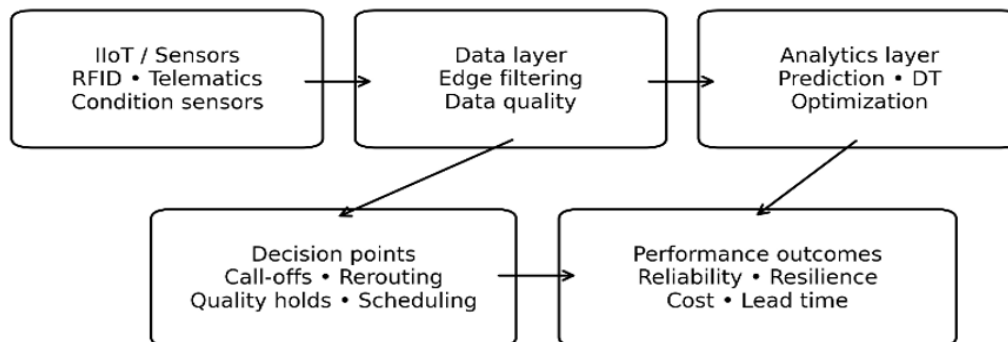


Figure 1 Conceptual positioning of IIoT-enabled sensor-to-decision pathways in automotive supply chains

2 Literature review

2.1 IIoT, Sensor networks, and digital twins in SCM

IIoT extends industrial connectivity to physical assets through sensing, networking, and computation. Sensor networks provide identity, location, and condition signals; digital twins increasingly serve as a decision layer by combining real-time data with analytical models. Recent 2025 work emphasizes supply chain digital twin design and analytics frameworks for connecting data to decision contexts [1,2], and reviews the role of digital twins in operational efficiency and risk management [3], including resilience improvement [4].

2.2 Decision relevance and operationalization

A recurring limitation is that technology capabilities are frequently treated as outcomes. For example, visibility is assumed to increase performance without specifying the decision point (what decision is taken, by whom, under what threshold). Frameworks for IIoT adoption and supply chain information management stress governance, information quality, and adoption conditions [5,6]. A mechanism perspective separates (i) capability (what is sensed), (ii) mechanism (repeatable operational pattern connecting signals to decisions), and (iii) performance impact.

2.3 Resilience, risk, and security as boundary conditions

Automotive supply chain research in 2025 continues to foreground resilience and risk. Risk prioritization approaches highlight the need for actionable decision support in automotive contexts [7]. At the same time, cybersecurity becomes a prerequisite for scaling IIoT-enabled SCM systems; analytics-driven security frameworks target this gap [8]. Sustainable SCM frameworks and ISO-based guidance.

3 Methodology

This study applies a structured literature review (SLR) combined with qualitative synthesis. The scope is restricted to English-language publications from 01.01.2025 to 31.12.2025, to enable a focused snapshot of recent mechanism and framework contributions.

Data sources and search strategy. Searches were conducted in Scopus (15.08.2025), Web of Science (16.08.2025), and IEEE Xplore (17.08.2025). The database-specific search strings combined IIoT/industrial IoT terms, sensor technologies (sensor networks, RFID, telematics), supply chain/logistics decision-support terms, automotive context terms, and mechanism/framework terms.

Screening and eligibility. The search yielded 53 records (Scopus: 13; WoS: 17; IEEE Xplore: 23). Records were exported to EndNote and de-duplicated (Find Duplicates); 14 duplicates were removed, leaving 39 unique records. Title/abstract screening excluded 22 records primarily due to lack of automotive specificity, absence of supply-chain decision relevance, peripheral use of IIoT/sensors, or missing operationalized mechanisms/frameworks. Seventeen full texts were assessed and four excluded due to missing sensor-to-decision chains, superficial automotive mentions, overlap without added value, or insufficient methodological transparency. The final sample includes 13 studies (7 journal articles, 6 conference papers).

Data extraction and synthesis. Included studies were coded using decision-relevant SCM performance dimensions (visibility/traceability, reliability, responsiveness, inventory/cost, asset utilization) and operational translation elements (sensor data type, processing/analytics, decision trigger, responsible role/function, and response routine). Evidence was synthesized into mechanisms defined as repeatable operational patterns that link IIoT capabilities to decisions and expected performance impacts.

Mechanism identification and framework derivation.

To ensure methodological transparency, the identification of the four mechanisms (M1–M4) followed a structured qualitative coding procedure.

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First, all included studies ($n = 13$) were systematically reviewed to extract decision-relevant elements describing how IIoT and sensor data were used in automotive supply chain contexts. Particular attention was given to passages describing operational decision points, decision triggers, analytics usage, and resulting logistics actions.

Second, an open coding process was conducted to identify recurring “sensor-to-decision” patterns. Codes were assigned to textual segments that described how sensing capability was translated into operational supply chain decisions. Examples of initial codes included real-time tracking, predictive maintenance alerts, dynamic replenishment adjustment, and disruption-response alerting.

Third, the initial codes were iteratively grouped into higher-level analytical categories representing similar operational decision logics. During this phase, overlapping codes were consolidated and compared across studies to identify recurring operational structures.

Finally, four mechanisms were derived based on three consolidation criteria:

- (1) the presence of a clear sensor-to-decision pathway,
- (2) recurrence across multiple studies, and
- (3) a distinct operational decision logic separating it from other mechanisms.

This process resulted in four recurring mechanisms:

- M1 – real-time visibility and traceability control,
- M2 – predictive asset and quality logistics,
- M3 – inventory–production synchronization, and
- M4 – event-driven logistics decision support.

The mechanisms therefore represent synthesized operational decision patterns observed across the reviewed studies rather than isolated technological applications.

Study selection summary (Table 1, Figure 2).

Table 1 Study selection summary (2025 SLR)

Step	Count (2025)
Records identified (Scopus + WoS + IEEE Xplore)	53
Duplicates removed (EndNote)	14
Records after de-duplication	39
Title/abstract screened	39
Excluded at title/abstract	22
Full-text assessed	17
Full-text excluded	4
Studies included in synthesis (Journal / Conference)	13 (7 / 6)

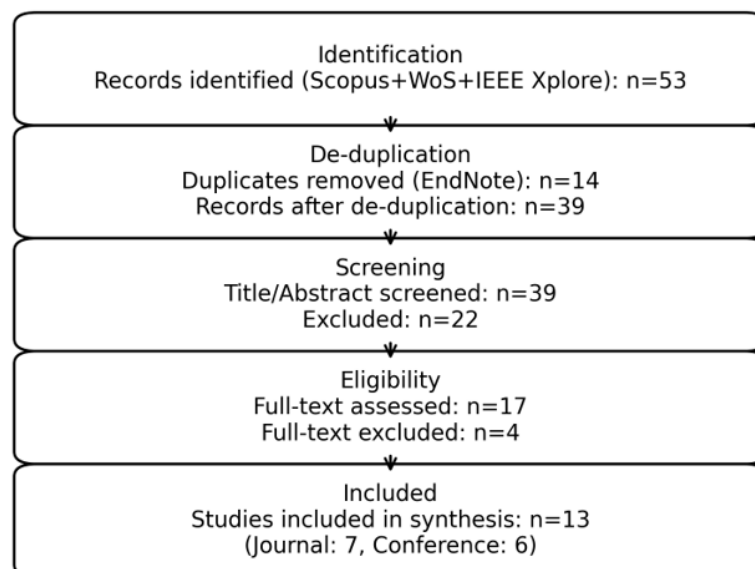


Figure 2 illustrates the PRISMA-based screening and selection process for the 2025 SLR

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3.1 Data extraction and coding procedure

We used a structured data extraction form to ensure consistent capture of “sensor-to-decision” elements across all included studies ($n = 13$). For each article, we extracted: (i) automotive context and supply chain scope (tier, node, or process), (ii) IIoT/sensor modalities and data characteristics (e.g., RFID, telematics, condition sensors; update frequency if reported), (iii) integration layer and systems interface (e.g., edge/cloud, middleware, ERP/WMS/TMS/MES touchpoints), (iv) analytics approach (e.g., prediction, optimization, digital twin, anomaly detection), (v) decision point(s) and triggering logic (what initiates a decision and who acts), and (vi) the intended or reported performance outcomes (e.g., lead time, service level, inventory accuracy, disruption impact, quality/reliability).

3.2 Synthesis approach

We synthesized evidence using a narrative synthesis combined with cross-case mapping. Narrative synthesis was used to describe how each study operationalizes sensor data for decision support in automotive supply chains, while cross-case mapping was applied to assign each study to one or more mechanisms (M1–M4) and to identify enabling conditions that recur across mechanisms. We report results at two levels: (i) mechanism-level insights (what the mechanism does and which decision points it targets), and (ii) cross-cutting enablers and boundary conditions (e.g., interoperability, governance, cybersecurity, organizational capability) that shape whether mechanisms can be implemented and scaled. This synthesis deliberately avoids inferring causal effects beyond what the reviewed studies explicitly report; instead, we focus on transparent mechanism descriptions that can guide implementation and future empirical testing.

To develop the mechanism framework, we applied an iterative coding strategy. First, we conducted open coding to identify recurring “data → analytics → decision” chains and operational decision triggers. Second, we grouped codes into higher-level categories that reflected the role of IIoT/sensor data in supply chain decision-making. Third, we consolidated categories into four mechanisms (M1–M4) by checking whether each mechanism represented (a) a distinct decision-relevant pathway, (b) a reproducible sequence from sensing to decision action, and (c) a defensible boundary to other mechanisms. Disagreements in coding were resolved through discussion and re-reading of the full texts until consensus was achieved. To illustrate the operational logic of the proposed mechanisms, consider a temperature-sensitive automotive component monitored via IIoT-enabled condition sensors. If a temperature threshold (e.g., $>8^{\circ}\text{C}$ for a defined duration) is breached during transport, the event is automatically transmitted to the integration layer and evaluated via predefined decision rules. If the threshold violation exceeds tolerance limits, a quality containment decision is triggered. The responsible quality manager receives an automated alert, and a hold status is posted in the ERP/QMS system. The shipment is flagged for inspection before further processing. This closed-loop structure (sensor signal → threshold logic → decision trigger → role assignment → system update → controlled response) operationalizes the sensor-to-decision pathway and clarifies how sensing capability translates into governed logistics action.

4 Results

Qualitative synthesis yields four recurring value-creation mechanisms. Each mechanism combines technology (sensing, connectivity, analytics) with process design (integration, governance, decision rights, and response playbooks). Where available, the 2025 literature provides decision-layer concepts such as digital twins and early-warning systems that exemplify ‘sensor-to-decision’ chains [1,2,9,10].

Across the included literature ($n = 13$), evidence clusters around four recurring sensor-to-decision pathways. While individual studies emphasize different technologies (e.g., RFID, telematics, digital twins), the reviewed contributions converge on a common structure: sensor data is integrated into enterprise decision contexts, transformed via analytics, and translated into concrete operational decisions (e.g., reallocation, replanning, quality containment, disruption response). We therefore present results as four mechanisms (M1–M4) and then synthesize cross-cutting enabling conditions that recur across mechanisms. From a logistics perspective, the four mechanisms can be interpreted as structured interventions into material flow control (M1, M3), transport coordination (M4), and production and quality logistics (M2). The framework therefore shifts the analytical focus from technological deployment to governed flow management across material, information, and financial coordination processes.

4.1 Mechanism 1: Real-time visibility and traceability

Identification technologies (e.g., RFID) and telematics improve the timeliness and granularity of state information (location, identity, status). Value is realized when visibility is embedded in closed-loop workflows: automated capture, exception detection, thresholds, and standardized escalation. Digital twin designs at scale illustrate how data models can support traceability and operational decision contexts [1], while adoption frameworks highlight the governance prerequisites for converting visibility into action [6].

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4.2 Mechanism 2: Predictive asset and quality operations

Condition and process sensors combined with analytics enable prediction of failures and deviations. Performance gains occur when predictive insights are integrated into maintenance planning and quality gates, shifting from reactive interventions to condition-based scheduling and targeted inspection/holds. Digital twin-based predictive quality assurance and resilience frameworks exemplify this integration layer in automotive contexts [9].

4.3 Mechanism 3: Inventory-production synchronization

Continuous inventory and consumption signals reduce latency between physical stock and planning records. When integrated into replenishment rules and allocation logic, these signals enable dynamic safety-stock adjustments and earlier detection of shortages. Knowledge-enhanced information management frameworks reinforce the role of high-quality information flows as a prerequisite for planning synchronization [5].

4.4 Mechanism 4: Event-driven decision support

IIoT platforms translate sensor events into actionable alerts through rule engines, workflow automation, and control-tower practices. Value is realized when thresholds, decision rights, and response playbooks are defined and governed. Early-warning systems for supplier delays illustrate decision-triggered alerting and probabilistic risk signals [10], while resilience-oriented literature motivates event-driven mitigation to reduce disruption impact [3,4,7].

4.5 Cross-cutting enabling conditions

Across mechanisms, three enabling conditions determine whether outcomes are realized: (i) interoperability and data governance (identifiers, master data, integration architecture, ownership), (ii) cybersecurity and data protection (secure onboarding, segmentation, monitoring), and (iii) organizational capability and decision rights (skills, training, authority to act). Security-focused frameworks explicitly address the governance gap for IIoT-enabled SCM systems [8]. ISO-based guidance and sustainability framing further shape how IIoT is designed and governed in practice [11-14].

4.6 Mechanism framework summary

The Architecture summarizes the proposed mechanism framework as a layered sensor-to-decision chain (Figure 3). The top row describes the technical pathway from sensing (IIoT/sensor data) to integration and analytics, while the bottom row groups the reviewed contributions into four decision-relevant mechanisms (M1–M4) (Figure 4). The framework is intentionally implementation-oriented: it highlights where data quality and interoperability constraints typically emerge (integration layer), where analytical capability is required (analytics layer), and where decisions must be operationalized via routines, roles, and playbooks (decision points) (Table 2). The cross-cutting enablers emphasize that technical readiness alone is insufficient; governance, cybersecurity, and organizational capability determine whether mechanisms can be scaled across automotive networks.

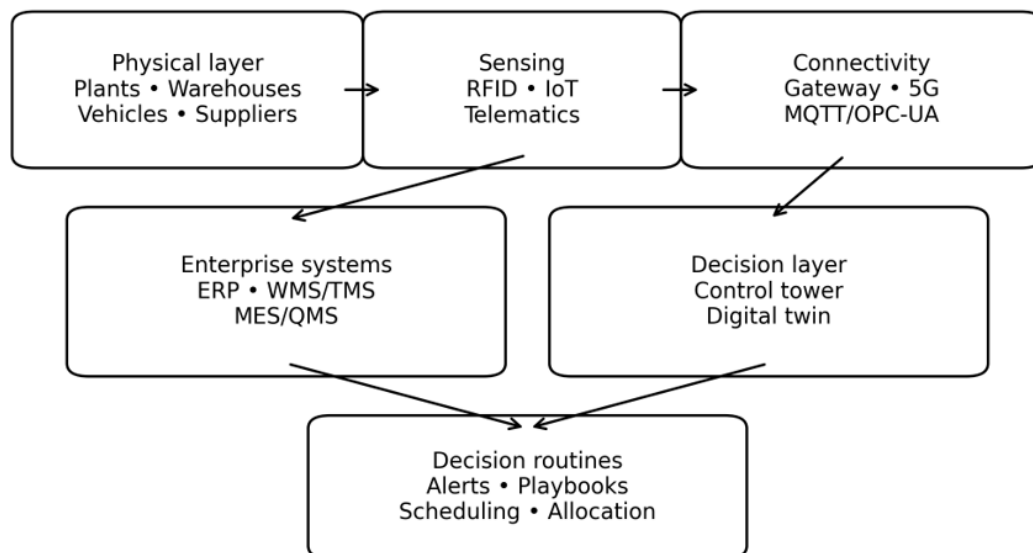


Figure 3 Reference architecture for sensor-to-decision integration in automotive supply chains

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Table 2 Mechanism framework linking sensor signals to automotive SCM decisions and impacts

IIoT/Sensor capability	Mechanism	Decision point	Expected impact	Key enablers
RFID, telematics, identification sensing	Visibility & traceability	Exception escalation (late/mismatch/loss)	↑ reliability, ↓ expediting	IDs/master data; integration; decision ownership
Condition/process sensors + analytics	Predictive asset & quality operations	Maintenance scheduling; quality hold/release	↓ downtime, ↓ defect propagation	Calibration; cybersecurity; authority
Consumption + inventory signals	Inventory–production synchronization	Replenishment parameters; allocation under constraint	↑ inventory accuracy, ↓ line-stops	Latency control; governance; ERP/WMS integration
Event processing + workflow automation	Event-driven decision support	Reroute/expedite/reschedule via playbooks	↑ responsiveness, ↓ disruption impact	Playbooks; decision rights; partner data-sharing

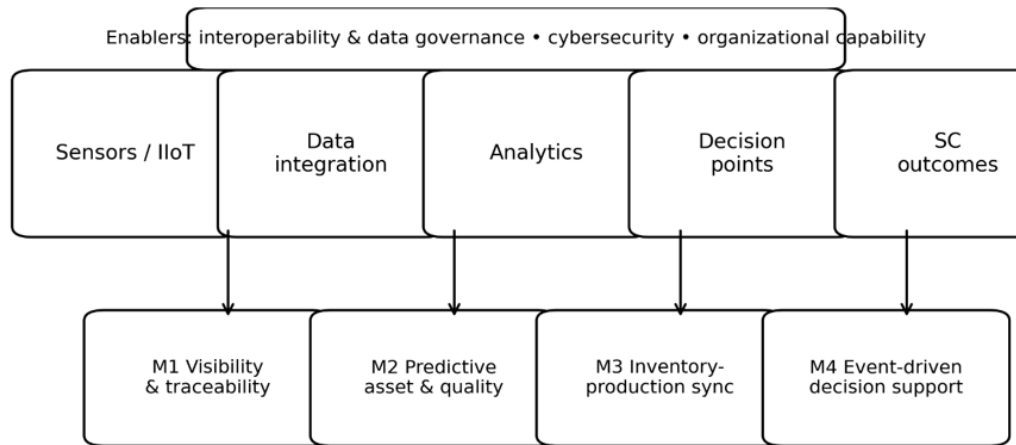


Figure 4 Sensor-to-decision mechanism framework synthesizing four recurring IIoT-enabled decision pathways (M1–M4) in automotive supply chains

5 Discussion

The mechanism framework clarifies why IIoT initiatives often under-deliver: sensing improves information, but performance improves only when signals are embedded into governed decision routines. Digital twin research strengthens the decision-layer perspective by formalizing data models and analytics contexts for operational decisions [1,2], and reviews consolidate evidence that digital twins can support risk management and resilience when appropriately governed [3,4]. At the same time, adoption and information management frameworks emphasize organizational and governance conditions, not only technology [5,6]. Unlike traditional visibility-oriented supply chain frameworks that primarily emphasize information transparency as an end state, the proposed model explicitly defines governed decision routines, operational triggers, and execution-layer integration. The novelty therefore does not lie in sensor deployment itself, but in formalizing reproducible decision pathways that connect sensing, analytics, and organizational authority. By separating capability, mechanism, trigger, and performance impact, the framework addresses a structural gap between technological readiness and executable supply chain control.

5.1 Managerial implications

This review suggests three actionable implications for managers aiming to implement IIoT- and sensor-driven decision support in automotive supply chains.

First, managers should start from a concrete decision point rather than from technology availability. Successful initiatives specify who decides (role), when a decision is triggered (threshold/event), which systems must be updated (ERP/WMS/TMS/MES), and how the response is executed (playbook). This reduces the common failure mode where sensor data is collected but does not translate into operational action.

Second, interoperability and master-data governance should be treated as core design requirements. Many sensor-to-decision chains depend on consistent identifiers (items, containers, locations, vehicles) and reliable event timestamps.

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Without a disciplined data governance model, analytics outputs cannot be trusted or operationalized across partners and tiers. Managers should therefore invest early in standardization (data dictionary, event schema, mapping rules) and in monitoring of data quality.

Third, organizations should align analytics capability with the maturity of decision routines. Where decision routines are immature, lightweight analytics and alerting (e.g., exception detection) can deliver value quickly by improving visibility (M1) and event response (M4). As routines mature, more advanced analytics (prediction, optimization, digital twin) becomes feasible and can support higher-impact decisions such as dynamic allocation, inventory–production synchronization, and disruption mitigation. Across all mechanisms, cybersecurity and access control are essential, because sensor-driven decision support expands the attack surface along the supply chain network. Overall, the mechanism framework can be used as a practical roadmap: firms can assess which mechanism they can realistically operationalize given their integration maturity, governance capability, and decision process readiness, and then scale stepwise toward more advanced decision automation.

5.2 Limitation and future research

This review has several limitations. First, the study deliberately focuses on literature published in 2025 to provide a high-resolution snapshot of current developments. While this supports timeliness, it limits longitudinal comparison and may underrepresent foundational work published earlier. Second, although the search strategy covered three major databases and applied explicit screening criteria, publication bias and database coverage bias cannot be fully ruled out. Third, the synthesis emphasizes mechanism transparency rather than meta-analytic effect estimation; the included studies vary in method, reporting depth, and evaluation setting, which constrains the ability to compare outcomes quantitatively. Future research can build on this review in three directions. (1) **Mechanism validation:** The proposed M1–M4 mechanisms should be empirically tested in real automotive networks (OEM–tier systems) using measurable decision outcomes (e.g., service level, lead time, disruption impact). Comparative designs could examine which enablers (governance, cybersecurity, organizational capability) moderate mechanism effectiveness. (2) **Decision-centric metrics and playbooks:** More work is needed on standardizing decision triggers, escalation paths, and playbooks that translate analytics into action. This includes defining KPI dictionaries and linking decision routines to system updates (ERP/WMS/TMS/MES), enabling replicable implementations. (3) **Cross-organizational integration and trust:** As sensor-to-decision chains increasingly span partners, research should address interoperability standards, data-sharing agreements, and security architectures that allow scalable collaboration without sacrificing confidentiality or resilience. Extending the review window beyond 2025 and incorporating multiple years would further support robustness and enable trend analysis across the evolving IIoT and digital-twin landscape. Future studies should operationalize the proposed mechanisms using measurable decision-level indicators, such as trigger frequency, decision latency, override rates, and post-decision performance impact. Linking sensor-to-decision execution logs with KPI outcomes would allow quantitative validation of mechanism effectiveness and comparison across automotive supply chain tiers.

5.3 Practical implementation checklist (decision-centric, sensor to decision)

This subsection translates the proposed sensor-to-decision mechanism framework into an implementation-oriented checklist. The checklist is decision-centric: it starts from concrete decision points and links them to sensing requirements, integration design, analytics capability, and operational response routines (playbooks). It is intended to support stepwise adoption across the four mechanisms (M1–M4) and to increase implementation transparency and reproducibility. The items can also be used as an assessment instrument to identify capability gaps before scaling across sites or partners.

Scope and decision design:

- ☐ Decision scope defined: which specific supply chain decisions will be improved (e.g., call-off adjustments, rerouting, quality containment, scheduling, inventory rebalancing).
- ☐ Decision owners assigned: RACI defined (owner, back-up, escalation path, approval authority).
- ☐ Decision timing specified: reaction time targets (minutes/hours/days) and operational cadence defined.
- ☐ Success criteria agreed: primary KPIs selected (service level, lead time, disruption impact, inventory accuracy, quality yield).

Sensing and data requirements:

- ☐ Sensor modalities selected and justified: RFID / telematics / condition sensors / scanning events (fit to the decision).
- ☐ Event schema defined: which events exist (e.g., arrival/departure, temperature breach, shock, machine state, quality flag).
- ☐ Refresh rate and latency targets defined for each event stream.
- ☐ Identifier consistency ensured: item/container/location/vehicle IDs standardized across partners and systems.

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- ☐ Data quality rules documented: completeness, timeliness, plausibility checks, deduplication, missing-event handling.

Integration and interoperability:

- ☐ System touchpoints identified: ERP / WMS / TMS / MES / QMS / control tower / digital twin.
- ☐ Mapping rules documented: sensor IDs ↔ master data ↔ transactional objects (orders, shipments, lots/batches).
- ☐ Interface design defined: protocols and pipelines (API, MQTT/OPC-UA, ETL/ELT, message bus).
- ☐ Data governance established: ownership of master data, change management, versioning, and auditability.
- ☐ Cross-organizational agreements clarified: data sharing boundaries, retention, access rights, and confidentiality.

Analytics and mechanism selection (M1–M4):

- ☐ Target mechanism selected: M1 visibility/traceability; M2 predictive quality/asset/operations; M3 inventory–production synchronization; M4 event-driven decision support.
- ☐ Analytics approach matched to maturity: alerting → prediction → optimization → digital twin (stepwise roadmap).
- ☐ Decision triggers defined: thresholds, anomaly rules, prediction confidence levels, scenario triggers (for digital twins).
- ☐ False positive/negative handling defined: suppression rules, confirmation steps, human override, and retraining cadence.

Decision operationalization (the sensor-to-decision link):

- ☐ Response playbooks written for each trigger: action steps, responsible role, communication steps, and required system updates.
- ☐ Execution-system updates specified: what must be posted/changed in ERP/WMS/TMS/MES/QMS for the decision to take effect.
- ☐ SLA and escalation set: time limits, fallback procedures, and escalation hierarchy defined.
- ☐ Human-in-the-loop policy defined: where manual approval is required and where automation is permitted.

Security and resilience (boundary conditions):

- ☐ Threat model documented: risks for sensor streams, gateways, APIs, and partner interfaces.
- ☐ Access control implemented: roles, least privilege, secret management, and logging.
- ☐ Integrity and auditability ensured: provenance, tamper detection (where feasible), and audit trails.
- ☐ Resilience plan defined: outage mode, buffering, replay strategy, and recovery procedures.

Measurement and continuous improvement:

- ☐ Baseline captured: pre-implementation KPI levels recorded.
- ☐ Monitoring set up: data quality dashboards and decision adoption metrics (how often playbooks are executed).
- ☐ Post-decision evaluation defined: KPI impact window and review cadence agreed.
- ☐ Scaling criteria defined: go/no-go thresholds for extending to additional sites/partners and mechanisms.

5.4 Research agenda and testable propositions

While the 2025 literature provides a broad set of technology- and application-driven contributions, it remains comparatively under-specified on how sensor and IIoT data is translated into reproducible decisions at scale across automotive networks. Future research should therefore move from technology-centric descriptions toward decision-centric operationalization and evaluation of the proposed mechanisms (M1–M4). In particular, empirical studies should test (i) which enabling conditions (interoperability, governance, cybersecurity, organizational capability) are necessary and sufficient for each mechanism, (ii) how decision routines and human-in-the-loop designs affect adoption and performance, and (iii) under which operational contexts (product mix, disruption profile, network structure) each mechanism yields the highest benefit. Based on the synthesized framework, we propose the following testable propositions:

P1 (Decision operationalization): IIoT initiatives that explicitly define decision triggers, decision owners, and response playbooks achieve higher decision adoption and sustained use than initiatives focusing primarily on sensor deployment and data collection.

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P2 (Data governance as moderator): The positive impact of sensor-based analytics on supply chain performance is strengthened by master-data quality and interoperability, particularly consistent identifiers, timestamps, and standardized event schemas across partners and systems.

P3 (Security as boundary condition): Cybersecurity maturity moderates the scalability of sensor-to-decision mechanisms; low security maturity increases implementation risk and reduces cross-organizational data sharing and adoption.

P4 (Mechanism–context fit): The performance effects of the four mechanisms (M1–M4) depend on the disruption and variability profile of the supply chain (e.g., visibility mechanisms are more valuable in high-variability transport networks, while predictive quality mechanisms yield greater benefits in quality-sensitive component flows).

P5 (Digital twin value conditions): Digital twin-based decision support delivers superior operational outcomes compared to non-twin analytics when closed-loop integration with execution systems (ERP/WMS/TMS/MES/QMS) and clearly defined decision routines are established.

P6 (Human-in-the-loop design): Mechanisms that combine automation with structured human oversight (e.g., exception-based approval and escalation rules) outperform fully manual or fully automated approaches in terms of robustness and organizational acceptance.

P7 (Cross-organizational trust and incentives): The effectiveness of sensor-to-decision mechanisms in multi-tier automotive networks increases when data sharing agreements, incentive alignment, and auditability mechanisms are in place, reducing information asymmetry and opportunistic behaviour.

These propositions provide a concrete basis for future empirical validation of the mechanism framework, including comparative multi-site studies, longitudinal designs, and mixed-method evaluations that link sensor-to-decision operationalization to measurable supply chain outcomes.

6 Conclusion

This study contributes a decision-centric mechanism framework that formalizes how IIoT and sensor networks translate into governed logistics decisions within automotive supply chains. Based on 13 included studies, four recurring sensor-to-decision mechanisms (M1–M4) were identified, clarifying how sensing, analytics, and governed decision routines influence material and information flow performance.

The theoretical contribution lies in formalizing sensor-to-decision pathways as reproducible logistics mechanisms rather than treating IIoT capability as an isolated technological upgrade. The framework emphasizes that logistics performance improvements emerge when sensing is embedded into structured decision triggers and execution routines.

For practitioners, the framework provides a roadmap for stepwise operationalization across visibility control, predictive logistics, synchronization of material flows, and event-driven disruption response.

Future research should empirically validate the mechanisms across multi-tier automotive networks and examine how governance, cybersecurity, and organizational capability moderate logistics performance outcomes.

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Integrating resilience and sustainability in supply chains: a strategic evaluation framework

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Abstract: Over recent years, global supply chains have been and continue to be under significant pressure resulting from major disruptions largely driven by the consequences of the COVID-19 pandemic, persistent geopolitical instability. Supply chains are also increasingly asked to undergo structural transformations to comply with rising sustainability requirements due to accelerating impacts of climate change. Although resilience and sustainability in supply chain and logistics have been largely studied, existing research mainly addresses the two concepts separately and offers limited frameworks to evaluate their simultaneous effects on logistics decision levels. This article proposes an evaluation framework to assess the joint impact of sustainability and resilience practices within organisations' supply chains. A dual methodological approach is adopted, combining a quantitative literature review using bibliometric analysis (Bibliometrix, Scopus database, 65 selected publications) with a qualitative content review of existing frameworks. Key supply chain practices are identified and classified across strategic, tactical, and operational decision levels, and their cross-impacts are evaluated on resilience and sustainability. The results reveal a structural pattern: Strong synergies between resilience and sustainability arise from practices optimising information flows, collaborative practices with stakeholders, circular and efficiency-driven processes. However, some unavoidable trade-offs are identified such as network diversification and multi-sourcing, inventory buffering, material-flow redundancy strategies and just-in-time management, which enhance resilience but increase resource consumption and transport emissions. The proposed framework offers a cross-impact evaluation tool for managers to assess supply chain resilience and sustainability performance within their organisations and prioritise implementation of strong synergy practices while mitigating trade-offs.

1 Introduction

Nowadays, companies are increasingly seeking strong, agile, and adaptive supply chains in order to manage, anticipate, and mitigate unexpected disruptions. Supply chains are strongly facing multiple uncertainties including climate change issues, geopolitical conflicts, global health crises such as COVID-19, and deep digital transformation under the growing influence of artificial intelligence. In this context, [1] states that developing resilience capabilities offers significant advantages for supply chain management enabling organisations to adapt effectively to disturbances and ensure the continuity of operations. Parallely, strong effects of climate change leading to environmental degradation, growing stakeholder pressure concerning environmental and social responsibility, human rights, and workplace safety have emphasized the need to adopt sustainability principles across all stages of supply chain management [2] and [3].

This integration increases environmentally friendly improvements, reduces waste generation, enhances resource efficiency, strengthens supplier relationships, and ultimately reinforces consumer trust. Approaches based on robustness—such as lean practices, digital enablers, agility, and visibility—can effectively strengthen supply chain resilience. However, they may also generate conflicts with some sustainability objectives. Therefore, the two concepts of resilience and sustainability must be strategically and smartly integrated into unified supply chain management frameworks [4]. [5] develop the concept of reconfigurability that has also been identified as a critical capability to cope with disruptions and adapt to rapid changes in market conditions.

Literature on supply chain resilience and sustainability has been growing significantly in recent years; however, most studies address these two concepts separately or in disconnected ways. Research on resilience topic focused mainly on strategies and tools to anticipate, face and recover from disruptions, while sustainability works focus on integration in supply chains strategies of environmental impacts, social responsibility, and economic viability. Only a limited number

of papers have literally examined the link between resilience and sustainability in supply chain management and even develop tools and frameworks to help evaluate their combined effects.

Main existing models deal separately with sustainability-oriented strategies and resilience-enhancing practices at supply chain strategic, tactical and operational levels. This separation limits the interest for decision-makers facing the challenge of balancing long-term sustainability goals with mid and short-terms resilience objectives.

Therefore, managers need an integrated framework that assesses key practices in supply chain management for both resilience and sustainability, highlights potential synergies and trade-offs and help managers to design and operate supply chains that are robust in the face of growing disruptions and aligned with sustainable development objectives.

This paper aims to develop an evaluation framework capable of identifying and assessing resilience and sustainability key practices across supply chain decision levels. This research adopts a dual methodological approach combining bibliometric analysis and qualitative synthesis of existing frameworks to identify key supply chain practices and evaluate their interaction effects.

The main objective of this study is to conceptualise and structure a Supply Chain Assessment Framework (SCAF) that classifies practices according to their combined impact on resilience and sustainability: Strong synergies, synergies and trade-offs.

Accordingly, this study addresses the following research questions:

- RQ1: How resilience and sustainability have been addressed simultaneously in supply chain management within the existing scientific literature?
- RQ2: Which supply chain key practices generate synergies or trade-offs between resilience and sustainability?
- RQ3: How can these interactions be structured in an evaluation framework that supports managers in building resilient and sustainable supply chains?

2 Literature review

2.1 Trends on relation between resilience and sustainability

Recent research highlights a growing focus on synergies and trade-offs between supply chain resilience (SCRE) and supply chain sustainability (SCS). While these two dimensions were traditionally examined separately, several authors argue that their integration has become critical to face the escalating global disruptions and increasing sustainability demands. [4] demonstrate that certain practices—such as collaboration, agility, and digital visibility—can simultaneously enhance resilience and sustainability, while strategies like redundancy or high inventory levels improve continuity but at the cost of higher resource consumption. Similarly, [6] show how digital supply chain twins (DSCTs) enable end-to-end visibility and simulation of disruption scenarios, thereby strengthening resilience while simultaneously reducing waste and improving environmental and social outcomes. Sector-specific studies also highlight this link. For example, [7] propose a framework for resilient agri-food supply chains in the UAE, showing how integrating resilience capabilities with sustainability objectives directly supports food security strategies under conditions of scarcity and global volatility. [8] further extend the debate by developing a performance measurement framework that links social sustainability indicators with resilience, emphasizing that resilience-oriented practices must also account for human resources, community welfare, and stakeholder participation. Technological enablers play a central role in this integration, [9] argue that digital twins at the supply chain system level can enhance both resilience through disruption risk management and sustainability through waste reduction and carbon monitoring, though challenges remain regarding standardized measurement frameworks. Empirical evidence provided by [10] confirms that many strategies (e.g., multi-sourcing, supplier partnerships) strengthen both resilience and sustainability, while others (e.g., relocation or diversification) may lead to conflicts increasing costs or emissions. More recent contributions extend the analysis to operational strategies. [11] emphasize that post-COVID-19 operations must integrate green–lean practices, circular economy models, and local sourcing to simultaneously improve resilience and deliver sustainability outcomes. In another 2025 contribution [12] propose the Integrated Sustainable Operational Strategy (ISOS), which unites circularity, localization, and digital adaptation across macro, meso, and micro levels, framing adaptive capacity as the new definition of operational excellence.

2.2 Existing models and gaps

Recent literature addressing the integration of resilience and sustainability within supply chain management shows a steady evolution from descriptive and static models toward dynamic, digital, and system-oriented frameworks (Table 1). The work of [4] introduced a conceptual model structured around performance management, risk, and resilience strategies, emphasizing synergies and trade-offs between redundancy and sustainability. [6] operationalized these interactions through a *Digital Supply Chain Twin* that enables simulation and decision-making under disruption scenarios. In a regionalized approach, [6] developed a food security framework tailored to the UAE context, combining indicators, analytical models, and big data to ensure resilient and sustainable agri-food systems. From a measurement perspective, [8] proposed the *Socially Responsible Performance Measurement (SRPM)* framework, integrating the SCOR model and

blockchain technology to capture social sustainability and resilience dimensions simultaneously. Similarly, [9] conceptualized a three-dimensional *Digital Twin* classification framework extending from manufacturing to entire supply chains, highlighting the interlinkages between efficiency, resilience, and sustainability. Building on empirical insights, [10] advanced an integrative SCRE–SCS framework grounded in the Resource-Based View and Contingency Theory, showing that resilience and sustainability can be mutually reinforcing under collaborative governance. Finally, [11] proposed the *Integrated Sustainable Operational Strategy (ISOS)* framework based on Dynamic Capabilities and the Triple Bottom Line, merging circularity, localization, and digital adaptation to achieve systemic transformation toward resilient–sustainable operations. Overall, these frameworks converge toward a systemic vision in which resilience is not merely reactive but a structural component of long-term sustainability.

Table 1 Summary of existing frameworks addressing integration of sustainability and resilience in supply chain management

Reference	Framework Type	Theoretical Foundation	Key Dimensions	Methods / Tools	Main Contributions
[4]	Integrated conceptual framework	Performance and risk management	Resilience (anticipation, resistance, recovery); Sustainability (economic, social, environmental)	Systematic Literature Review (232 articles)	Integrates resilience and sustainability through performance, risk, and strategic alignment.
[6]	Simulation-based (Digital Supply Chain Twin)	Digital engineering; decision-making under uncertainty	Resilience and triple-bottom-line sustainability	Simulation (AnyLogistix)	Operationalizes resilient–sustainable strategies via digital twin simulation.
[7]	Food Security Analytical Framework	Systems thinking; food policy integration	Food security, resilience, sustainability	Indicators, scenario analysis, big data platform	Provides early-warning and vulnerability monitoring for sustainable agri-food systems.
[8]	SRPM (Socially Responsible Performance Measurement)	Resource-Based View; SCOR model; Blockchain technology	Social, economic, and resilience dimensions	Valuation methods (avoided cost, productivity, damage assessment)	Joint measurement of social sustainability and resilience impacts using digital transparency.
[9]	Digital Twin Framework	SCOR model; hierarchical supply chain systems	Efficiency, resilience, sustainability	Classification (digital model, shadow, twin)	Extends digital twin applications to system-level supply chains integrating sustainability goals.
[10]	SCRE–SCS Integration Framework	Resource-Based View; Contingency Theory	Strategies, barriers, metrics for SCRE–SCS integration	Mixed-method study (survey of 143 executives)	Empirical framework linking resilience and sustainability as complementary strategic capabilities.
[11]	ISOS (Integrated Sustainable Operational Strategy)	Dynamic Capabilities Theory; Triple Bottom Line; Systems Thinking	Circularity, localization, digital adaptation	Conceptual model with illustrative cases	Multi-level framework connecting resilience, sustainability, and industrial transformation.

3 Methodology

Research Design: This study adopts a dual approach including quantitative bibliometric analysis and qualitative content deep screening to assess the integration of resilience and sustainability in supply chains and logistics. The research process aims to design a framework to identify, classify and synthesise key supply chain practices generating synergies and trade-offs between resilience and sustainability dimensions.

Data Collection and selection criteria: The bibliometric analysis was conducted using the Scopus database, due to its broad coverage of peer-reviewed journals in supply chain, logistics and sustainability. The following search query was

applied on 28 November 2025 to “Keywords” index to capture studies explicitly addressing the intersection between resilience concept and sustainability in supply chain, with a framework perspective:

“Supply chain” AND “sustainab*” AND “resilien*” AND “framework” *

After screening abstracts for relevance to the subject, 65 documents were retained for final analysis.

Inclusion criteria: Explicit focus on both resilience and sustainability, framework orientation, supply chain and logistics context.

Exclusion criteria: articles focusing only on resilience or sustainability and papers unrelated to frameworks.

Bibliometric analysis: The selected dataset (65 documents) was analysed using Bibliometrix (R package) with focus on key outputs such as Annual scientific production, most relevant sources and most frequent keywords. The quantitative mapping provides an overview of the intellectual structure and maturity of the research field.

Quantitative content analysis: Following bibliometric mapping, a qualitative content analysis was conducted to identify recurring supply chain practices and classify them according to

- Decision level
- Resilience practices
- Sustainability practices

Practices were extracted manually and cross-checked across frameworks to determine their accuracy. Each practice was evaluated according to its directional impact on resilience and sustainability (positive, neutral, negative) allowing classification into:

- Strong synergy (positive – positive)
- Synergy (positive – neutral or vice versa)
- Trade-off (negative – neutral or vice versa)
- Strong trade-off (negative – negative)

To reduce subjectivity, classification decisions were based on explicit arguments found in the reviewed literature.

4 Results

4.1 Bibliometrix results

The output dataset of the bibliometric research comprised 65 documents covering the period 2012–2025, with a notable concentration of publications emerging after 2020.

Annual production: Annual production data show a sharp increase in contributions since 2024, with 13 articles in 2024 and 25 articles in 2025 (up to 28 November 2025) reflecting the growing interest of integrated approaches to global disruptions and sustainability challenges (Figure 1). In more detail, annual scientific production trends on supply chain resilience, sustainability, and frameworks, based on Scopus data up to 28 November 2025 shows very limited research activity between 2012 and 2020, with no more than three publications per year. From 2021 onwards, the number of studies increased steadily with four papers in 2022 and six papers in 2023. The real increase in interest started in 2024 with 13 papers. This trend is continuing in 2025 with 25 articles published until the 28th of November. This sharp growth shows the rising academic and managerial importance of developing conceptual frameworks that link resilience and sustainability in supply chain management. It also demonstrates that the topic has moved from a niche research area into a mainstream scholarly concern, driven by recent global disruptions and sustainability pressures.

Most Relevant Sources: The most relevant sources include *Sustainability (Switzerland)*, *Journal of Cleaner Production*, and *Review of Management Literature*, highlighting the diversification nature of this research domain (Figure 2). The results indicate that research is mainly concentrated in a limited number of journals, with *Sustainability (Switzerland)* emerging as the dominant journal, contributing with 11 articles to the panel which represents 17% of the set selected. *Journal of Cleaner Production* and *the Review of management literature* follow with 4 publications. *Sustainable Development* and *Computers and Industrial engineering* with 3 publications each. *Environment, development and sustainability*, *Ifac papersonline*, *Journal of environmental management*, *Procedia computer science* and *Resources, conservation and recycling* and with 2 publications each. The distribution highlights both the multidisciplinary nature of the topic with environmental management, industrial engineering, operations management and circular economy—and the growing relevance of sustainability and cleaner production journals as leading platforms for the field of this scope.

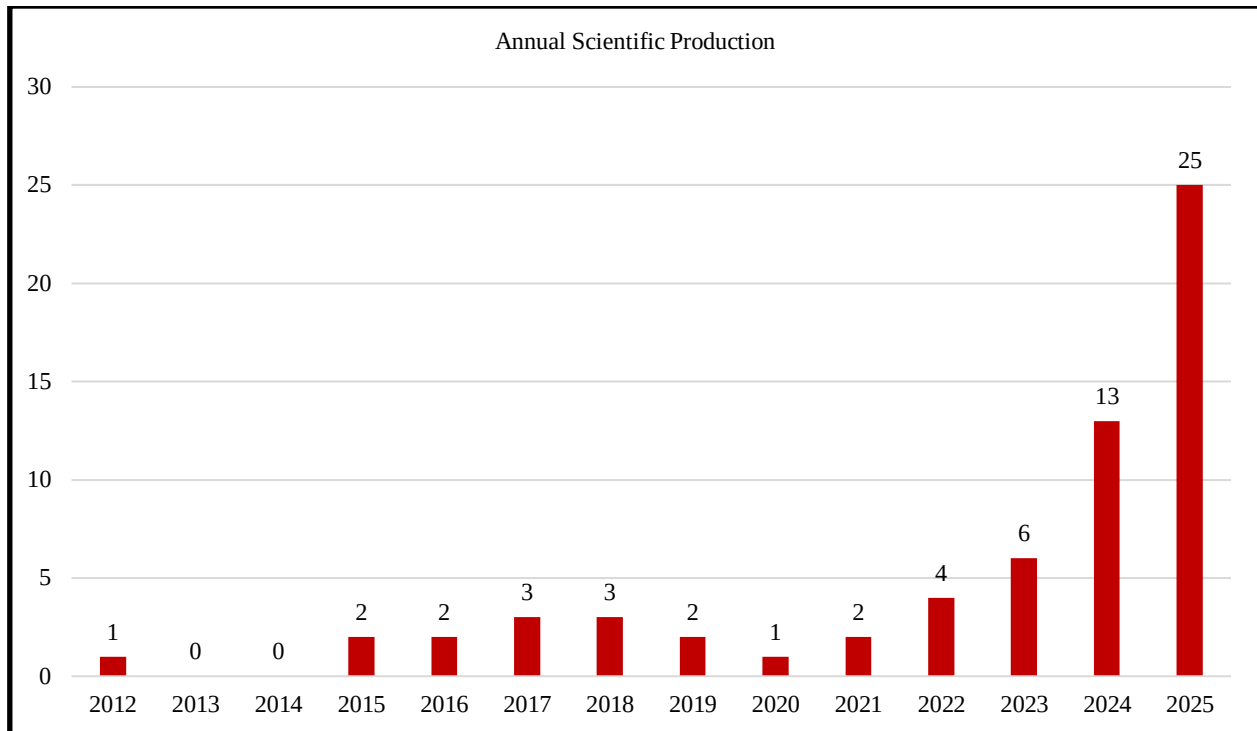


Figure 1 Annual scientific production

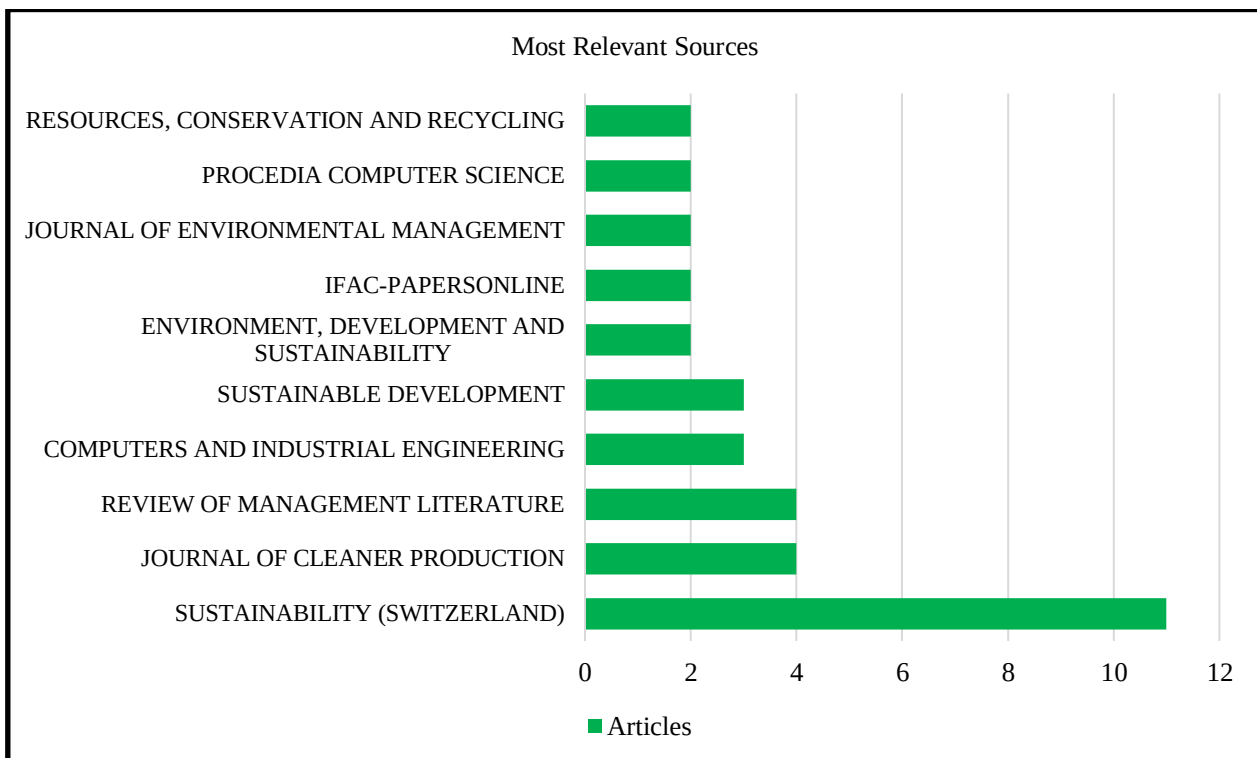


Figure 2 Most relevant sources

Most Frequent Words: Keyword analysis revealed strong clustering around “supply chain management,” “sustainability,” “resilience,” “conceptual framework” and “decision making” (Figure 3). The distribution of the most frequently occurring keywords within the Scopus dataset of November 28th, 2025, on supply chain resilience and sustainability frameworks reveals that “supply chain management” and “sustainability” dominate the panel with 34 occurrences each. “resilience” and “sustainable development” nearly follows with 33 occurrences each “Conceptual framework” and “conceptual frameworks” together appears 26 times in this review highlighting the academic trends to

structure investigations through theoretical and integrative models. “Supply chains” with 23 occurrences, “supply chain resilience” 13 occurrences, “supply chain resiliences” 9 occurrences and “supply chain” 7 occurrences emphasize the diverse formulations used to describe supply chain resilience related capabilities.

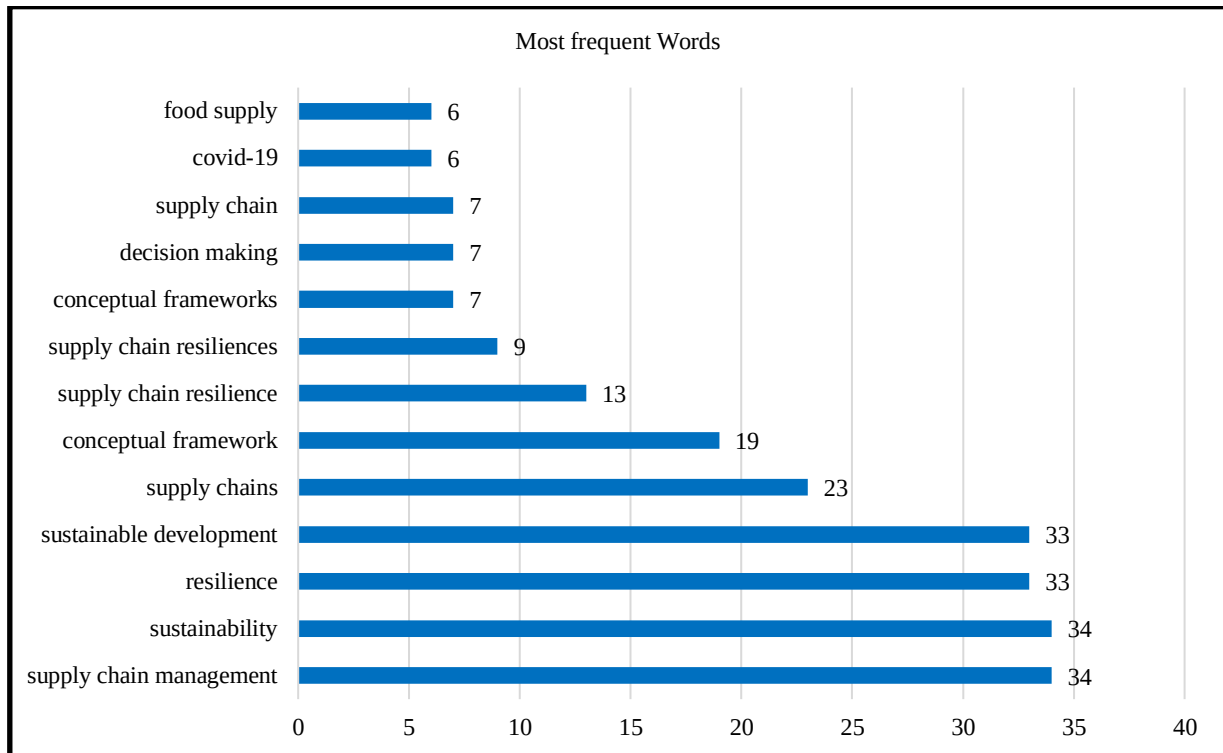


Figure 3 Most frequent keywords

4.2 Proposed strategic evaluation framework

The Proposed Supply Chain Assessment Framework SCAF provides an approach for assessing resilience and sustainability in supply chain management that will support companies’ management decisions in building strong and sustainable supply chains. In the first step, the SCAF classifies supply chain practices across strategic, tactical, and operational levels. In the second step the impact of resilience and sustainability is classified positive, neutral or negative. In the third step, the practice is identified as a Strong Synergy when the two impacts are positive; it is identified as synergy if one impact is positive and the other is neutral; it is identified as trade-off if one of the impacts is negative; the last case is when the two impacts are negative, then the practice is considered as a strong trade-off.

SCAF dimensions: Table 2 shows the three dimensions of the framework and their description.

Table 2 SCAF dimensions

Dimensions	Description
Decision Levels	Strategic, Tactical, and Operational levels
Resilience Capabilities	Adaptive and transformative capacities ensuring continuity and recovery from disruptions.
Sustainability Dimensions	Environmental, social, and economic performance consistent with the Triple Bottom Line.

SCAF Strategic Level assessment: Table 3 shows that at the strategic level, Strategic partnerships & collaboration with stakeholders and Digital transformation & Artificial Intelligence analytics emerge as strong integrators, Compliance with Regulatory Policies increase synergies while Network diversification and multi-sourcing strategies is identified as a trade-off.

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Table 3 SCAF strategic level assessment

Strategic Practices	Resilience Impact	Sustainability Impact	Synergies / Trade-offs
Strategic partnerships & collaboration with stakeholders	Positive: Reinforces relational resilience and knowledge sharing	Positive: Improves social sustainability (trust, inclusion)	Strong Synergy
Network diversification and multi-sourcing	Positive: Increases redundancy and flexibility	Negative: May increase carbon footprint due to longer logistics routes	Trade-off
Digital transformation & Artificial Intelligence analytics	Positive: Enhances visibility and anticipatory capability	Positive: Supports energy efficiency, waste reduction, transparency	Strong Synergy
Compliance with Regulatory Policies	Neutral: Ensures legal stability but does not improve ability to adapt, recover, or respond to disruptions.	Positive: Set environmental and social standards and drive proactive sustainability efforts.	Synergy

SCAF Tactical Level assessment: At tactical level, Supplier development programs and Localization of key suppliers' practices are strong integrators. Development of process agility and flexibility, adoption of Circular economy practices and Risk management are also important integrators practices. Inventory buffering represents a trade-off since it increases energy and resource consumption (Table 4).

Table 4 SCAF tactical level assessment

Tactical Practices	Resilience Impact	Sustainability Impact	Synergies / Trade-offs
Supplier development programs	Positive: Improves recovery capacity and redundancy	Positive: Promotes local employment and social welfare	Strong Synergy
Localization of key suppliers	Positive: Reduces exposure to global disruptions	Positive: Lowers transport emissions	Strong Synergy
Process Agility and Flexibility	Positive: Reduces process variability	Neutral: Does not inherently contribute to sustainability.	Synergy
Inventory buffering	Positive: Enhances robustness against demand shocks	Negative: Increases waste and storage energy consumption	Trade-off
Circular economy adoption	Neutral: Builds adaptive capacity through reverse logistics	Positive: Reduces resource consumption, promotes eco-efficiency	Synergy
Risk Management	Positive: Helps identify, assess, and mitigate risks proactively, reducing vulnerability and enhancing preparedness.	Neutral: Does not directly drive sustainability improvements unless explicitly focused on environmental and social factors.	Synergy

SCAF Operational Level assessment: At operational level, Lean manufacturing practices and Artificial Intelligence tools are strong integrators. Energy-efficient production scheduling and Preventive maintenance using IoT sensors are also important integrators practices. High inventory levels and just in time management represents a trade-off since it increases energy and resource consumption (Table 5).

Table 5 SCAF operational level assessment

Operational Practices	Resilience Impact	Sustainability Impact	Synergies / Trade-offs
High inventory levels	Positive: Enables fast recovery	Negative: May generate idle capacity and resource waste	Trade-off
Just-in-Time management	Negative: Minimizes inventory, making supply chains highly vulnerable to disruptions.	Neutral : Reduces waste and excess inventory, it can also increase frequent transportation, leading to higher carbon.	Trade-off

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Energy-efficient production scheduling	Neutral: May impact adaptive flexibility	Positive: Reduces carbon emissions	Synergy
Lean manufacturing development	Positive: Enhances efficiency and flexibility, reducing waste and improving adaptability in crises.	Positive: Focuses on waste reduction and efficient resource use, lowering the environmental impact of production.	Strong Synergy
Preventive maintenance using IoT tools	Positive: Prevents disruptions and downtime	Neutral: May reduce material waste and extends asset life	Synergy
Artificial Intelligence	Positive: Enhances predictive capabilities, allowing faster responses to disruptions.	Positive: Enhances resource efficiency and predictive maintenance, reducing waste and energy consumption.	Strong Synergy

Framework visualisation: Table 6 helps visualisation the framework by illustrating the relationship between Resilience and Sustainability across three organisational levels: Strategic, Tactical, and Operational. It is divided into five columns representing different degrees of alignment between resilience and sustainability:

- Horizontal Axis: Shows a continuum from Resilience (left) to Sustainability (right). Columns indicate whether actions create trade-offs or synergies between resilience and sustainability.
- Vertical Axis: Divided into three organisational levels. Strategic Level, Tactical Level and Operational Level
- Colour Coding:
 - Red: Trade-Off actions / Orange: Synergy actions / Green: Strong Synergy actions

Table 6 Framework visualisation

	Trade-Off: Resilience Oriented	Synergy: Resilience Oriented	Strong Synergy: Both Resilience & Sustainability	Synergy: Sustainability Oriented	Trade-Off: Sustainability Oriented
Strategic Level	Network diversification and multi-sourcing		Strategic partnerships & collaboration with stakeholders Digital transformation & Artificial Intelligence analytics	Compliance with Regulatory Policies	
Tactical level	Inventory buffering	Process Agility and Flexibility Risk Management	Supplier development programs Localization of key suppliers	Circular economy adoption	
Operational Level	High inventory levels	Preventive maintenance using IoT tools	Lean manufacturing development Artificial Intelligence	Energy-efficient production scheduling	Just-in-Time management

5 Discussion

5.1 Framework managerial contribution

The Supply Chain Assessment Framework (SCAF) identifies which practices strengthen both resilience and sustainability simultaneously, practices that enhance only resilience without decreasing sustainability and vice-versa and also clarifies where conflicts and trade-offs arise. On strategic level, the findings confirm that the strategic partnerships and collaboration with stakeholders create stronger synergy as it reinforces relational resilience and knowledge sharing and also improves social sustainability through trust and inclusion. digital transformation and AI analytics also create stronger synergies since they enhance visibility and anticipatory capability and support transparency. Compliance with regulatory policies also emerges as a synergy as it ensures legal stability but does not necessarily improve ability to adapt, recover, or respond to disruptions. On the other hand, practices like network diversification and multi-sourcing, remain a

trade-off as they protect against market disruptions but can conflict with sustainability goals through higher resource consumption. On tactical level, SCAF identifies practices like supplier development programs and localization of key suppliers as Strong Synergy since they improve recovery capacity and redundancy, promote local employment and social welfare, reduce exposure to global disruptions and lower transport emissions. Practices like process agility and flexibility, inventory buffering, circular economy adoption and risk management are identified as synergies since they reduce process variability and waste, build adaptive capacity, assess and mitigate risks. However, the findings point out inventory buffering as a persistent trade-off as it increases waste, storage capacities and energy consumption. On operational level, lean manufacturing development and AI emerge as strong synergies by enhancing efficiency, flexibility and predictive capabilities while focusing on waste reduction and efficient resource use. Energy-efficient production scheduling and preventive maintenance with IoT tools emerge as a synergy by reducing carbon emissions and waste and preventing disruptions and downtimes. By contrast, high inventory levels and just-in-time (JIT) management illustrate two opposite forms of trade-offs since it generates idle capacities and increases frequent transportation leading to higher carbon emissions and environmental degradation.

The findings highlight an important structural insight stating that synergies tend to cluster around practices that enhance collaboration, information flow using AI tools, circularity, and process efficiency, while trade-offs often arise from practices that rely on material and logistics redundancy.

This interpretation is consistent with the systemic understanding of distribution and supply logistics, where logistics performance depends on the coordinated management of material, information and financial flows across strategic, tactical and operational levels [13].

5.2 Framework implementation

To help the implementation of the Supply Chain Assessment Framework (SCAF), we suggest to start the process by assessing supply chain with regards to resilience and sustainability. This will link the conceptual framework to managerial decision-making. The following steps outline the main stages and conditions for effective application within organisations' supply chain.

Step 1 – Define Scope of the supply chain to assess: Organisations should begin by clearly delimiting the boundaries of their supply chain system (e.g., activity, process extent, geographic, and key partners).

Step 2 – Mapping of Practices: Managers should identify existing supply chain practices within their organisations and boundaries identified in step 1. Then classify them as strategic, tactical, and operational levels and map them to the SCAF:

- Practices such as Strategic partnerships & collaboration with stakeholders, Network diversification and Multi-sourcing, Digital transformation & Artificial Intelligence analytics and Compliance with Regulatory Policies will be classified as strategic.
- Supplier development programs, Localization of key suppliers, Process Agility and Flexibility, Inventory buffering, Circular economy adoption and Risk Management will be classified as Tactical practices.
- High inventory levels, Just-in-Time management, Energy-efficient production scheduling, Lean manufacturing development, Preventive maintenance using IoT tools, Artificial Intelligence will be classified as operational practices.

Step 3 – Data Collection: Managers should collect quantitative and qualitative data on each practice to help assess implementation of such practice. Quantitative Data could be collected through existing KPI within the organisation. Additional data could be gathered from external sources, sectorial analysis or through qualitative questionnaires.

Step 4 – Assessment: For each identified practice, managers evaluate the degree of influence on resilience capabilities and sustainability dimensions (economic, environmental, and social) and state whether this practice is implemented, to be enhanced or to be mitigated. Table 3, Table 4 and Table 5 can be used to qualify synergies and/or trade-offs.

Step 5 – Conditions for successful implementation:

- Leadership Commitment: Executive support ensures that resilience–sustainability integration becomes an organisational priority rather than a short-term project.
- Cross-Functional Collaboration: Integrating sustainability and resilience requires the active participation of multiple departments (procurement, operations, logistics).
- Monitoring, Learning, and Continuous Improvement the SCAF should not be treated as a static assessment tool but as a dynamic management mechanism.

5.3 Limitations and future research

Resilience and sustainability to be addressed jointly: Given the growing complexity of global supply chains, resilience and sustainability should be integrated simultaneously rather than treated separately or as competing objectives. A joined approach enables companies to address both short-terms objectives resilience oriented and long terms objectives sustainability oriented.

Strong synergies exist between resilience and sustainability: Collaborative partnerships, supplier development, digital transformation, and circular economy initiatives simultaneously strengthen resilience capacities and enhance sustainability performances. These synergies align short-term responsiveness with long-term sustainability goals.

Structural trade-offs remain unavoidable and must be mitigated: Despite existing synergies, certain trade-offs persist. Practices that enhance resilience—such as diversification or inventory buffering—may increase environmental impacts, whereas lean and just-in-time approaches improve sustainability but heighten vulnerability. These tensions require balanced strategic management.

The Supply Chain Assessment Framework (SCAF) as the core contribution: SCAF offers a dual approach that simultaneously assess resilience and sustainability across strategic, tactical, and operational levels. It helps visualise interactions, prioritize high- and medium-synergy practices, and mitigate unavoidable trade-offs.

Limitations and directions for future research: Although useful, SCAF remains conceptual and lacks empirical validation. Future studies should operationalize it through measurable indicators and composite indices. Additionally, sector-specific differences are not fully captured, indicating the need for comparative analyses across industries and regions.

6 Conclusion

This article highlights the need to assess supply chain resilience and sustainability together, rather than treating them as separate or competing objectives. Through a combination of quantitative bibliometric analysis and qualitative review of existing frameworks, this article shows that academic interest in resilience–sustainability integration emerged significantly since 2020, especially since 2024. Existing studies mostly focus on conceptual alignment or specific tools. To address this gap, this article introduces the Supply Chain Assessment Framework (SCAF).

The main contribution of this article is the development of the SCAF, which introduces a cross-impact evaluation logic based on decision level and flow-based practices assessment.

The findings reveal strong synergies cluster around practices enhancing flows, collaboration, digitalisation, circularity and process efficiency, whereas trade-offs typically stem from material-flow redundancy, logistics network diversification, multi-sourcing and inventory buffers.

From a managerial perspective, SCAF enables managers to design more resilient and sustainable supply chain configurations. However, the framework remains conceptual and needs empirical validation through KPIs and also sector and region-specific applications.

Overall, the research advances a more integrated, balanced and systemic perspective on resilient and sustainable supply chain management.

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AI agents for decision support in logistics management: a literature review

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Keywords: intelligent agents, multi-agent systems, logistics management, supply chain, resilience.

Abstract: The increasing complexity, volatility, and sustainability pressures affecting global supply chains have accelerated the adoption of Artificial Intelligence (AI) technologies in logistics management. Among these AI approaches, Intelligent Agents (IAs) and Multi-agent Systems (MAS) have emerged as essential tools for supporting decentralized, adaptive, event-driven, and real-time decision-making processes in dynamic logistics environments. Unlike traditional centralized planning systems, agent-based approaches enable autonomous entities such as suppliers, warehouses, transportation units, and distribution centers to coordinate actions, exchange information, and manage variability. This paper presents a structured literature review of peer-reviewed studies indexed in Scopus and Web of Science on the use of AI agents to support decision-making in logistics management and supply chain operations. Particular attention is given to the strategic importance of intelligent agents in strengthening resilience, operational efficiency, and sustainability in increasingly uncertain logistics systems. The findings indicate that intelligent agents improve decision quality, responsiveness, coordination, and resource utilization across distributed logistics networks. Furthermore, Multi-Agent Systems enhance interoperability and collaboration among logistics actors, enabling more agile and resilient supply chains. However, challenges related to data quality, cybersecurity, governance, scalability, and human–AI collaboration continue to limit large-scale implementation in industrial environments.

1 Introduction

Logistics systems are exposed to increasing uncertainty derived from demand variability, supply disruptions, geopolitical tensions, climate-related events, and sustainability requirements. Traditional centralized planning tools often struggle to respond in real time to events across distributed networks of suppliers, carriers, warehouses, and customers [1].

Within the broad field of Artificial Intelligence (AI), Intelligent Agents (IAs) and Multi-Agent Systems (MAS) have emerged as promising paradigms for modeling logistics operations in dynamic and distributed environments. Agent-based systems enable autonomous entities to interact, exchange information, and coordinate decisions in response to changing operational conditions. In logistics and supply chain contexts, agents may represent suppliers, transportation units, warehouses, planners, or organizations capable of coordinating actions to achieve local and global objectives. Through these interactions, Multi-Agent Systems support flexibility and responsiveness in supply chain operations under uncertainty, making them relevant approaches for modern logistics management [2].

Foundational work highlights that transportation and supply chain planning problems are natural candidates for distributed decision architectures [3]. More recent reviews also show a broad spectrum of MAS applications for planning, coordination, and control across supply chains [4].

In parallel, advances in data infrastructure, IoT, cloud computing, and reinforcement learning have enabled more sophisticated agentic AI, in which software agents continuously sense, reason, and act on large volumes of operational data. Empirical studies and conceptual analyses suggest that intelligent agents will increasingly orchestrate cross-functional supply chain decisions, autonomously executing operational choices within predefined constraints [5].

This paper addresses the following research question:

How do AI-based agents support decision-making in logistics management, and what benefits, limitations, and research gaps have been identified in the Scopus and Web of Science literature and in other aspects?

2 Methodology framework

2.1 Literature search strategy

This study employed a structured literature review approach based on peer-reviewed journal articles and conference proceedings retrieved from the Scopus and Web of Science (WoS) databases. The search focused on studies that address the application of AI agents in logistics decision-making contexts. The initial database search retrieved approximately 64,600 records.

The search strategy used combinations of keywords associated with intelligent agents, logistics, and decision-making, which were applied to titles, abstracts, and author keywords:

(“Intelligent agent” OR “software agent” OR “multi-agent system” OR “agent-based”)
AND
(“logistics” OR “supply chain” OR “transportation” OR “warehouse” OR “inventory”)
AND
(“decision making” OR “decision support” OR “planning” OR “scheduling”)

Titles and abstracts were screened, excluding records that did not address AI agents or logistics decision-making as central topics. Of the remaining 125 full-text articles assessed for eligibility, 65 were excluded due to insufficient agent-based information, purely descriptive scope, or lack of decision-making focus. Therefore, 60 records identified through snowballing and manual searches of key journals were incorporated, resulting in a final corpus of core papers, which were subjected to thematic synthesis and coding.

The time window was open (from the earliest available to 2025) to capture both foundational MAS work and recent applications of agentic AI in operations.

Additional articles were identified by snowballing from the reference lists of key papers and scanning recent volumes of logistics and operations journals.

2.2 Study selection criteria

The selected studies met the following conditions:

- addressed logistics or supply chain operations (transportation, warehousing, inventory, production scheduling, risk management, humanitarian logistics);
- used AI agents, MAS, or agent-based models as a central modeling or implementation paradigm;
- focused on decision making (planning, scheduling, routing, allocation, risk mitigation) rather than purely descriptive simulation.
- Works limited to conceptual discussions of Industry 4.0 or Logistics 4.0 without explicit agent models, or purely predictive models without autonomous decision making, were excluded or used only as contextual background.

2.3 Analysis and synthesis

The selected articles, 60 core papers, were coded along the following dimensions:

- Logistics function and decision level (strategic, tactical, operational, and real-time execution).
- Agent architecture type (single-agent, MAS, hybrid with centralized coordinator).
- AI techniques employed (rule-based agents, reinforcement learning, metaheuristics, fuzzy-rough sets, Bayesian networks).
- Application context (urban logistics, container terminals, Ro-Ro terminals, warehouses, production systems, humanitarian supply chains).
- Reported benefits and limitations associated with AI-agent implementation in logistics decision-making.

A thematic synthesis was then conducted to identify recurring patterns in how AI agents support logistics decision-making, the benefits obtained, and limitations reported (Table 1):

Table 1 Articles 60 core papers

Ref.	Reference	Logistics Function & Level	Agent Architecture type	AI Technique	Implemented?	Key Benefits	Key Limitations
[1]	Baryannis et al. (2019)	Risk mgmt tactical	MAS	AI + DSS hybrid	No	Risk insights	Low empirical validation
[2]	Kaihara (2003)	SC modeling tactical	MAS	Optimization agents	No	Dynamic modeling	High abstraction
[3]	Wadhwa & Bibhushan (2006)	SC modeling tactical	MAS	Simulation	No	Clear models	No deployment
[4]	Dominguez & Cannella (2020)	SC control tactical	MAS	Rule-based	No	Clear MAS structure	No field validation

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[5]	Xu et al. (2021)	SC automation strategic	–	MAS	Automation agents	No	Automation roadmap	Theoretical
[6]	Singh (2003)	SC coordination strategic	–	Single agent	Knowledge-based agents	No	Foundational framework for agent roles in information systems	Conceptual only; no logistics-specific validation
[7]	Herzog & Timm (2021)	Smart logistics operational	–	MAS	Learning agents	No	Knowledge adaptation	No pilot application
[8]	Grundspenkis (2008)	Logistics automation operational	–	MAS	Knowledge-based	No	Conceptual strength	No empirical data
[9]	Govindu & Chinnam (2007)	SC coordination tactical	–	MAS	Rule-based	No	Collaboration gains	Not tested
[10]	Akanle & Zhang (2008)	SC design strategic	–	MAS	Optimization + heuristics	No	Flexible SC design	Complex calibration
[11]	Julka et al. (2002)	SC decision support – tactical	–	MAS	Agent-based modeling framework	No	Integrated multi-enterprise decisions	Tested only in refinery DSS prototypes
[12]	Shukla & Kiridena (2016)	SC configuration tactical	–	MAS	Fuzzy-rough agents	No	Multi-criteria modeling	Parameter tuning
[13]	Böhllein et al. (2011)	Transport planning – tactical	–	MAS	Heuristic coordination	Yes	Efficiency gains	Data integration effort
[14]	Schleiffer (2002)	Traffic control operational	–	MAS	Reactive agents	Yes	Flow improvement	Older data
[15]	Bazzan et al. (2005)	Traffic routing operational	–	MAS	Reinforcement + rules	Yes	Adaptive routing	Scalability issues
[16]	Kahalimoghadam et al. (2025)	Last-mile operational	–	MAS	RL agents	No	Routing improvements	Not deployed
[17]	Helo & Rouzafzoon (2023)	Timber logistics operational	–	MAS	Simulation + optimization	Yes	Improved routing	Context specific
[18]	Salas-Rodríguez & Rivas-Tovar (2022)	Transport infrastructure tactical	–	MAS	Simulation	No	Scenario modeling	No RL
[19]	Kmjaic et al. (2024)	Warehouse order picking operational	–	MAS	Hierarchical multi-agent RL	No	Higher pick rates than heuristics	Simulation-based evaluation
[20]	Um et al. (2010)	SC coordination tactical	–	MAS	Rule-based	No	Coordination modeling	No validation
[21]	Li & Epureanu (2020)	Fleet allocation operational	–	MAS	Simulation heuristics	No	Allocation gains	Model complexity
[22]	Terrada et al. (2020)	SC management tactical	–	MAS	Hybrid	No	Structured approach	No field test
[23]	Chen et al. (2013)	SC risk operational	–	MAS	ABM	No	Disruption modeling	No live pilots
[24]	Bugert & Lasch (2023)	Risk propagation tactical	–	MAS	Bayesian + ABM	No	Deep risk modeling	High computational cost
[25]	Nadi et al. (2023)	Slot mgmt execution	–	MAS	Data-driven agents	Yes	Delay reduction	Terminal-specific
[26]	Rodríguez-Espíndola et al. (2023)	HL optimization – strategic	–	MAS	ABM	No	HL insights	No implementation
[27]	Liao et al. (2023)	Humanitarian structures operational	–	MAS	Simulation	No	Structure insights	No implementation
[28]	Rezki & Mansouri (2024)	Supplier risk tactical	–	Single agent	ML/DL	No	Better prediction	High data demand
[29]	Davidsson et al. (2005)	Transport chains operational	–	MAS	Simulation agents	No	Chain understanding	No RL integration
[30]	Espejo-Díaz (2020)	Humanitarian IRP – tactical	–	MAS	Simulation + heuristics	No	Robust scenarios	No deployment
[31]	Hernández et al. (2009)	Collaboration tactical	–	MAS	Negotiation agents	No	Better coordination	High model complexity
[32]	Li & Chan (2013)	Dynamic SC tactical	–	MAS	ABM	No	Adaptive behaviors	No industry case
[33]	Xu et al. (2024)	Autonomous SC – strategic	–	MAS	Agent architecture + toolkit	No	Implementation methodology	Single case study
[34]	Jaimez-González & Luna-Ramírez (2021)	SCM architecture – strategic	–	MAS	Hybrid	No	Clear architecture	Not implemented
[35]	Lujak et al. (2021)	Traffic coordination operational	–	MAS	Control agents	Yes	Higher flow efficiency	Requires IoT

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[36]	Mes et al. (2013)	Real-time routing – execution	MAS	Learning heuristics	+	Yes	Fast re-routing	Data dependency
[37]	Gerrits et al. (2024)	Self-organizing transport strategic	MAS	Review typology	+	No	Autonomy–cooperativity framework	Conceptual
[38]	Moreno et al. (2025)	Pickup–delivery – execution	MAS	Simulation + ML		No	Routing optimization	Simulation only
[39]	Nitsche et al. (2023)	Autonomous logistics – tactical	MAS	Hybrid		No	MAS roadmap	No validation
[40]	Pal (2015)	Transport corridors – tactical	MAS	Simulation		No	Corridor insights	Simplified behaviors
[41]	Staruch (2023)	Production planning – operational	MAS	Smart agents		No	Better planning	Prototype only
[42]	Swaminathan et al. (1998)	SC dynamics – strategic	MAS	Negotiation agents		No	Foundational model	No implementation
[43]	Ulmer (2020)	Same-day routing – execution	Single agent	RL + heuristics		No	Adaptive decisions	Needs live data
[44]	Labelle & Frayret (2023)	Reverse logistics – tactical	MAS	ABM		No	Forecasts voluntary return rates	Region-specific data
[45]	Parmaksizoglou et al. (2025)	Marine terminals – operational	MAS	Multi-agent optimization heuristics	+	No	Coordinated berth and truck scheduling	Computational tests only
[46]	Henesey et al. (2009a)	Terminal AGV systems – operational	MAS	Agent-based simulation		No	Cost-efficient AGV configurations	Simulation only
[47]	Reddy et al. (2017)	Food procurement & cross-docks – operational	MAS	Negotiation agents + PSO		No	Less food waste; better routing	Case-specific
[48]	Macal & North (2010)	SC modeling – strategic	Single agent	ABM methodology		No	Strong methodology	Generic focus
[49]	Henesey et al. (2009b)	Container terminal ops – operational	MAS	Agent-based simulation		No	Shorter ship turnaround	Terminal-specific
[50]	Bastarion et al. (2023)	Urban transport – tactical	MAS	Bibliometric review of ABM		No	Map of research clusters	Calibration/validation gaps
[51]	Espejo-Díaz & Guerrero (2021)	Post-disaster relief – tactical	MAS	ABM optimization	+	No	Better service levels	Single case (Mocoa)
[52]	Fan et al. (2021)	Cold chain design – strategic	MAS	Agent-oriented simulation		No	Cost–emission–quality trade-offs	Single product case
[53]	Feng et al. (2022)	Ride-sourcing & transit – execution	Single agent	RL + integer programming		No	Better matching efficiency	Simulation with city data
[54]	Fikar et al. (2018)	Disaster relief distribution – operational	MAS	ABS optimization	+	No	Improved relief planning	Scenario-based
[55]	Kaddoussi et al. (2013)	Crisis scheduling – SC operational	MAS	Distributed scheduling agents		No	Coordinated delivery	Simulation only
[56]	Mes & Douma (2016)	Barge–terminal appointments – operational	MAS	Multi-agent planning		No	Higher terminal utilization	Simulation with port data
[57]	Hernández et al. (2014)	SC collaboration – tactical	MAS	Negotiation agents		No	Service level and profit gains	One automotive SC
[58]	Chan et al. (2012)	Air cargo – operational	MAS	Agents simulated annealing	+	No	Faster load planning	Prototype system
[59]	Li & Ni (2022)	Rail timetabling – operational	MAS	Multi-agent deep RL		No	Flexible timetabling	Computational tests only
[60]	Zhou et al. (2019)	Ride-hailing dispatch execution	MAS	Multi-agent RL		Yes	Decentralized dispatching	Platform-specific data

Note: MAS = Multi-Agent System

3 Theoretical background

3.1 Intelligent agents and multi-agent systems

In the field of Artificial Intelligence (AI) intelligent agents are autonomous software-based entities capable of perceiving environmental conditions, processing information, and acting to achieve specific objectives [6,61].

Intelligent agents and MAS have been widely applied in manufacturing, logistics, and transportation since the 1990s as a form of distributed artificial intelligence [7,8].

Multi-Agent Systems consist of autonomous agents that interact and cooperate to address complex and distributed problems. These systems are particularly suitable for dynamic environments in which information and decision-making processes are decentralized and require coordinated responses among multiple actors [9]. Several papers explicitly argue that logistics and supply chain management constitute natural domains for MAS due to the presence of numerous autonomous actors and the need for negotiation, contracting, and coordination [3].

3.2 Decision support and agentic AI in logistics

Traditional Decision Support Systems (DSS) in logistics rely on centralized optimization and planning models. While powerful, these architectures may struggle with real-time responsiveness, inter-organizational coordination, and scalability [10].

Agent-based decision support addresses these limitations by distributing decision capabilities among agents representing carriers, warehouses, orders, vehicles, or even market platforms. MAS can be combined with optimization, simulation, and machine learning to build intelligent decision support systems that learn from data while preserving the autonomy of distributed actors [4,11-13].

In logistics, this translates into agent-based transport planning, dynamic routing, distributed inventory decisions, production scheduling, and risk management [2,14].

4 Applications of AI agents in logistics operations

4.1 Transportation and last-mile logistics

Transportation has been one of the earliest and most developed domains for MAS in logistics. Agent-based and multi-agent models represent vehicles, customers, and infrastructure, negotiating delivery schedules and routing plans under constraints such as time windows and capacity [15,16].

Recent work proposes intelligent MAS for city logistics and last-mile delivery, where agents coordinate parcel deliveries, micro-hubs, and crowdsourced couriers in highly dynamic urban environments [16].

These systems incorporate real-time traffic conditions, customer preferences, and environmental constraints to optimize routing and consolidation decisions, often through combined simulation–optimization approaches [17,38]. In addition, multi-agent decision support has been developed for transportation regulation and traffic management, where agents model regulators, drivers, and infrastructure to propose control strategies [35,62]. Agent-based simulation has also been used to study the co-evolution of logistics clusters and the transfer of knowledge among the firms that compose them [63].

4.2 Warehousing, picking, and inventory management

In warehousing, agent-based decision support has been applied to order picking and to the coordination of robotic and human workers. Krnjaic et al. [19] develop a hierarchical multi-agent reinforcement learning approach in which a manager agent assigns picking tasks to robot and human worker agents, improving pick rates and sample efficiency relative to heuristic baselines across several warehouse layouts and both person-to-goods and goods-to-person picking paradigms.

Minashkina and Happonen [64] systematically review the literature that links Warehouse Management Systems (WMS) with social and environmental sustainability. Searching Scopus and Web of Science for the period 2006–2022, they identify only 12 relevant articles, published between 2013 and 2022 in business, engineering, computer science, and the social sciences. The review finds that social sustainability receives more attention than environmental sustainability, that the Internet of Things and Industry 4.0 technologies are recurring themes, and that integrating WMS with complementary systems supports warehouse sustainability objectives.

Agent-based and multi-agent models are also proposed for multi-echelon inventory control, where agents monitor stock levels across facilities and negotiate orders and replenishment policies to mitigate the bullwhip effect [2,20]. Fuzzy–rough sets and other AI techniques are integrated into multi-agent analytics frameworks to configure supply chains and inventory strategies in dynamic environments [12].

4.3 Production, maintenance, and material management

In production and material management, MAS supports production scheduling, maintenance planning, and material flow control. Multi-agent system architectures have been proposed to coordinate production orders, machine agents, and logistics agents under dynamic demand and disturbances [9,41].

Agent-based models have also been applied to improve supply chain design and configuration processes, as well as modular vehicle fleets, integrating production and logistics decisions [10,21]. Multi-agent analytics frameworks facilitate the configuration of distributed manufacturing networks based on multiple-criteria performance measures [12].

4.4 Resilience, risk management, and humanitarian logistics

A growing body of work uses MAS to enhance supply chain resilience and risk management. Chen et al. [23] review agent-based modeling for supply chain risk, concluding that Agent-based Modeling and Simulation (ABMS) and MAS are well-suited to capture cascading disruptions and adaptive behaviors. They examine how ABMS has been applied to Supply Chain Risk Management (SCRM), arguing that traditional methods struggle to capture the complexity, interactivity, and adaptability of modern supply networks. Through a multi-perspective survey, the authors classify existing ABMS research along three dimensions: risk-management processes (identification, assessment, response, and monitoring/evaluation), planning decision levels (strategic, tactical, and operational), and supply chain design goals (robustness and flexibility). The researchers highlight that while ABMS provides significant advantages—such as modeling distributed autonomous agents, heterogeneous interactions, and dynamic disruptions—it remains under-utilized in SCRM studies, and more work is needed.

Similarly, Bugert and Lasch [24] combined agent-based modeling with Bayesian networks to analyze risk propagation within supply networks. Their findings demonstrate how local disruptions can spread both upstream and downstream throughout the supply chain.

Likewise, Nadi and others [25] developed a multi-agent decision support system for time-slot allocation at container terminals. The proposed system explicitly models agents' reactions to disturbances and uncertainty, enabling more efficient logistics operations management.

In humanitarian logistics, Rodríguez-Espíndola and others [26] conduct a systematic review of 105 articles on optimization models, assessing how effectively decision-makers (practitioners) are involved in model design and deployment. The authors find that only about 10% of studies actively engage practitioners in modeling decisions, and fewer than 22% propose new solution methods that deliver results within practical decision-making time horizons. The objectives in existing models often diverge significantly from the priorities of field practitioners, and environmental concerns are inadequately incorporated, despite being a top global agenda item. The review demonstrates that limited practitioner engagement and long computation times hinder real-world implementation of optimization models in humanitarian logistics. Accordingly, the authors advocate for more inclusive modeling processes, faster solution methods, and broader incorporation of sustainability and environmental objectives to enhance relevance and adoption.

Liao and others [27] developed an agent-based simulation model to compare three post-disaster humanitarian logistics structures: Agency-Centric Efforts (ACEs), Partially Integrated Efforts (PIEs), and Collaborative Aid Networks (CANs). The study examines how agent behaviors, including affected individuals, relief organizations, and shelters, and coordination mechanisms, such as information sharing and crowd movement, influence the performance of relief distribution systems. The results indicate that higher distribution capacity and advanced coordination mechanisms, particularly in CANs, significantly reduce deprivation costs and waiting times for affected populations. Although information sharing improves system performance, its marginal benefits gradually diminish. Additionally, restricting crowd movement through temporary shelters reduces demand uncertainty and enhances supply chain responsiveness.

These studies demonstrate how agents representing relief organizations, facilities, vehicles, and affected populations can support decision-makers in exploring alternative response strategies and evaluating trade-offs among speed, coverage, and equity.

5 Cross-cutting benefits and challenges

5.1 Reported benefits

Recent studies demonstrate that Multi-Agent Systems deliver measurable operational benefits across diverse logistics environments. González-Cancelas and others [65] propose a structured MAS architecture for Roll-on/Roll-off terminal management in which six specialized agents handle space allocation, route planning, traffic control, and boarding coordination. Their comparative analysis against traditional port management models indicates that agent-based automation can reduce vehicle dwell time by up to 25%, minimize unnecessary travel through dynamic routing, and improve ramp utilization through synchronized scheduling. Beyond efficiency gains, the study highlights that MAS integration supports sustainability objectives by lowering energy consumption and aligning terminal operations with Industry 4.0 principles of real-time decision-making, interoperability, and decentralized coordination. Across the reviewed literature, the main benefits of AI agents for logistics decision-making are:

- Improved responsiveness and real-time adaptation. MAS can react to local events without requiring global re-optimization, enabling more agile responses to disruptions [16,62].
- Handling of complexity and distribution. Agent-based models decompose large logistics systems into interacting entities, thereby improving scalability and enabling heterogeneous decision rules [5,13].
- Enhanced resilience and robustness. Agents facilitate scenario analysis and self-healing behaviors, in which logistics networks reconfigure routes, capacities, and sourcing in response to disruptions [25-27].
- Support for collaboration and privacy. Several architectures maintain detailed data locally while sharing aggregated information or decisions through agent interactions, which is crucial for inter-organizational supply chains [65].

- Scalability and modularity. New agents (e.g., additional warehouses, carriers, terminals) can be added with limited changes to the system, supporting incremental deployment [14,39].

5.2 Challenges and limitations

Key challenges highlighted in the literature include:

- Integration with legacy systems. Many logistics operations rely on ERP, WMS, and TMS platforms; therefore, integrating MAS-based decision modules requires interoperability standards and robust APIs [9,22].
- Data quality and availability. Agentic AI depends on reliable and timely data. Data gaps or inconsistencies may compromise decision-making processes, particularly when learning-based agents are employed [28].
- Model validation and explainability. Validating agent behavior and explaining recommendations to human operators are essential, especially in safety-critical operations [5,23,24].
- Governance and accountability. As agents evolve from advisory roles to autonomous decision-making, organizations must establish clear governance frameworks, operational constraints, and accountability mechanisms for AI-driven decisions [66].
- Human-AI collaboration. Several studies emphasize the importance of designing interfaces, escalation mechanisms, and training processes that enable planners to understand, override, or refine agent recommendations. The literature also warns against both overreliance on and distrust of autonomous systems, highlighting the importance of training, interpretability, and shared control. Finally, the authors propose a research agenda focused on the responsible and human-centered adoption of AI in supply chains [67].

6 Results and discussion

Analysis of the 60 core papers reveals that the majority remain at early stages of empirical validation. Of the reviewed studies, 8 (13%) report deployment or pilot implementation in real operational settings, while the remaining 52 (87%) are conceptual, simulation-based, or limited to controlled experimental environments. This distribution reflects a persistent gap between theoretical agent-based models and industry-ready decision-support tools, and highlights the need for more applied research bridging this divide.

Regarding agent architecture, the reviewed literature shows a clear dominance of Multi-Agent Systems, which account for 55 of the 60 studies (92%), while single-agent approaches represent the remaining 5 (8%). This distribution reflects the inherently distributed and interdependent nature of logistics operations, where coordination among multiple autonomous entities, each managing a specific function such as routing, scheduling, or inventory control, offers greater flexibility and scalability than centralized single-agent designs.

The reviewed studies span all three levels of logistics decision-making, though with uneven coverage. Operational and tactical decisions are the most frequently addressed, each appearing in 22 studies (37%), followed by strategic decisions in 10 (17%) and execution-level applications in the remaining 6 (10%). The relative underrepresentation of strategic-level applications suggests that AI agent deployment remains closer to day-to-day operational optimization than to long-term network design or policy decisions, pointing to an area where future research could expand the scope of agent-based contributions.

A notable diversity of AI techniques is observed across the reviewed studies. Simulation and agent-based modeling (ABM) are the most frequently applied approaches, each appearing in 4 studies, followed by rule-based systems, negotiation agents, and hybrid approaches, each appearing in 3 studies. The remaining papers employ a wide range of methods, including heuristics, hybrid models, Bayesian learning, neural networks, and machine learning. Grouping these into broader categories, simulation-based techniques account for approximately 37% of the corpus, while learning-based approaches, including reinforcement learning and machine learning variants, represent around 18%, reflecting a gradual shift toward data-driven methods in more recent contributions.

A temporal analysis of the 60 core papers reveals a clear upward trend in research output. Publications before 2015 account for 23 studies, while those from 2015 to 2025 contribute the remaining 37, with a pronounced acceleration after 2019: the years 2020, 2021, and 2023 alone account for 20 papers (33% of the total corpus). This growth coincides with broader advances in machine learning, increased availability of real-time logistics data, and the disruptions to global supply chains triggered by the COVID-19 pandemic, all of which appear to have intensified academic interest in intelligent, adaptive decision-support systems.

7 Conclusions

This paper reviews the literature on AI agents for decision support in logistics operations. The reviewed studies indicate that intelligent agents and Multi-Agent Systems (MAS) provide a promising paradigm for addressing the complexity, dynamism, and distributed nature of modern logistics systems. Applications across transportation, warehousing, production, and resilience management demonstrate significant potential to enhance responsiveness,

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efficiency, and robustness. However, the literature also highlights persistent challenges related to system integration, data management, governance, and human–AI collaboration.

The reviewed literature suggests that most agent-based models rely on simplified structures, static assumptions, or hypothetical datasets, which limit empirical validation and reduce practical decision-support value. Several authors emphasize the need for more data-driven ABMS frameworks that integrate real-time sensor data, digital twin inputs, and stochastic demand signals to improve model fidelity, calibration, and industrial applicability.

Existing studies rarely capture how disruptions propagate across multi-tier networks or how autonomous agents collaborate, negotiate, and adapt within dynamic risk environments. According to the literature, distributed coordination mechanisms, including decentralized optimization, cooperative game theory, and reinforcement learning, may improve the simulation of emergent behaviors and adaptive resilience strategies across global supply chains.

The reviewed applications frequently operate in isolation, with limited integration of structured risk frameworks, scenario-based planning, and optimization-based mitigation models. Based on the identified gaps, future research should consider incorporating frameworks such as ISO 22301, Business Continuity Management Systems (BCMS), ISO 31000, Risk Management Guidelines, and ISO 28000, Security Management in the Supply Chain. Furthermore, several studies suggest developing hybrid approaches that integrate ABMS with robust optimization, agent-based decision support, and risk-aware planning systems to evaluate mitigation strategies, quantify resilience, and support real-time decision-making under uncertainty.

Significant gaps identified in MAS and humanitarian logistics research include limited practitioner involvement: approximately 10% of studies incorporate decision-makers into model design. The literature suggests that future research should promote the co-creation of models with humanitarian practitioners by incorporating their objectives, constraints, and operational preferences early in the modeling lifecycle, thereby increasing the relevance and adoption of these systems. On the one hand, several studies report that existing solution methods often lack practical timeliness, with fewer than 22% delivering results within decision-sensitive timeframes. Consequently, there is a need for faster, more scalable optimization algorithms that can deliver actionable solutions during crises rather than relying solely on offline methods. On the other hand, environmental and sustainability objectives remain insufficiently integrated into humanitarian logistics models despite their growing global relevance. The reviewed studies suggest that this limitation may be addressed by incorporating environmental sustainability indicators — such as carbon emissions, circular logistics, and resource scarcity — together with multi-criteria decision-making approaches that balance humanitarian, economic, temporal, and ecological objectives.

Overall, the literature suggests that intelligent agents and multi-agent systems constitute a powerful yet underexplored paradigm for humanitarian logistics, disaster risk reduction, and resilience building. Nevertheless, most existing applications remain conceptual or simulation-based and continue to focus primarily on traditional commercial supply chains. Future research should therefore focus on designing, implementing, and empirically validating agent-based systems capable of supporting end-to-end humanitarian logistics operations, including early warning systems, needs assessment, pre-positioning strategies, dynamic allocation of scarce resources, and last-mile delivery under conditions of extreme uncertainty. In addition, several authors emphasize the importance of integrating risk information, climate scenarios, and social vulnerability indicators into agent architectures to improve continuity planning before, during, and after disruptive events. The literature also highlights the importance of developing human-centered agents that collaborate with emergency managers, local communities, and non-governmental organizations (NGOs), rather than replacing them, in order to ensure the legitimacy, transparency, and ethical use of AI technologies. Ultimately, advances in agent-based decision support may contribute not only to faster and more efficient emergency responses but also to long-term resilience and the protection of lives and livelihoods in the face of recurrent crises.

Finally, the reviewed studies emphasize the importance of developing hybrid architectures that incorporate human-centered design principles and ESG-oriented performance metrics. Future developments in agentic AI are expected to reshape decision-making and coordination processes across logistics networks by enabling more adaptive, collaborative, and data-driven operations. In this context, future research may focus on integrating intelligent agents with real-time analytics, digital twins, sustainability frameworks, and risk-aware planning systems to improve resilience and operational responsiveness. Moreover, the literature suggests that human-centered AI systems capable of supporting, rather than replacing, human decision-makers could play a critical role in humanitarian logistics, disaster response, and complex supply chain management. Ultimately, advances in agent-based decision support may contribute to more efficient, transparent, and resilient logistics systems under increasingly uncertain and dynamic environments.

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Evaluating the mediating role of information sharing between the main drivers and performance in the Moroccan automotive supply chain

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<https://doi.org/10.22306/al.v13i3.816>**Evaluating the mediating role of information sharing between the main drivers and performance in the Moroccan automotive supply chain****Fatima Ezzahra Boussehaib**Abdelmalek Essaadi University, Av. Mohamed El Kharraz, Tétouan, 93000, Morocco,
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Abstract: Companies are reaping the advantages of integration mostly through information sharing. The main goal of this study is to develop an empirical model based on results from Meta Analytic Review, in order to explain the impact of five explanatory variables from existing literature (Trust, Legal Contract, Commitment, Power, IT Capacity) on Financial and Non-Financial Performance via the mediating variable (Information Sharing) across the Moroccan Automotive Supply Chain. The choice of the Moroccan Supply Chain is based on the very limited and underdeveloped existing literature. To fill this gap, we conducted a questionnaire on a sample of 100 employees working in 'Tangier Automotive City'. Using SPSS 28.0 software, we attempt to verify the reliability and validity of the measurement scales. Subsequently, we proceeded to test the hypotheses via the structural equation modelling method with the help of the Smart PLS software. The results show the effect of the studied variables on sharing of information. They also show how important sharing information is for improving supply chain performance. This research fills a vacuum in the literature by using real-world examples from a developing nation and giving Moroccan managers useful advice on how to improve cooperation in the supply chain.

1 Introduction

Today, the economy is growing so fast, and the world is becoming more competitive and globalized. In this context, supply chains need to be more coordinated, responsive, and efficient. In fact, Supply Chain Management has changed from looking at the chain from inside _a single function_ to looking at it from the outside, including all the chain's stakeholders. This vision for integration stresses the need for all partners to coordinate their efforts to achieve shared objectives. This logic makes operations more efficient, saves costs, and allows all partners to respond more quickly to market needs. However, before the supply chain can be integrated, a couple things need to be in place: all partners must be able to share data in real time, and information must be easy to find. To meet these two requirements, the chain's stakeholders must agree to share information with each other. In this setting, exchanging information has become a keyway to improve overall performance and make it easier for supply chain partners to work together. Being able to provide fast, accurate, and useful information lowers uncertainty, risks, and helps everyone in the supply chain make better decisions.

Even while sharing information is important for strategy, it is still not done uniformly, especially in developing countries where there are still structural, technical, and social barriers. Morocco is a concrete example of this problem. The proof that the Moroccan literature review in this regard was very limited. In this regard, the purpose of this study is to delve into the international literature to critically examine the findings of these studies by contrasting them with the reality of the empirical data from the Moroccan Automotive industry.

This way of looking at things will enable us to add to the literature on the information exchange in the Moroccan supply chain. As a result, for Moroccan academics and students who want to do in-depth research on a related topic, our findings and the gaps indicated can serve as research pathways. Thus, the conclusions could be useful for Moroccan businesses that are currently debating the value of this approach in the managerial setting.

In this light, the concern of our study seeks to respond to two principal questions: "what is the effect of each factor on the degree and the frequency of sharing information between Moroccan Automotive supply chain participants?" In this work logic, we suggest examining any potential connections between the key explanatory factors from the literature (Trust, Legal

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contract, IT capacity, Commitment, and Power), and the mediating factor (Information Sharing). With the aforementioned factors in mind, we then ask: "How much does this sharing affect the financial and non-financial performance of the mentioned channel?"

Accordingly, our study model will be formed by breaking down these interactions into seven hypotheses, as presented in (Figure 1).

- H1: Trust has a significantly positive impact on information sharing in the supply chain.
- H2: The legal contract positively affects sharing information in the supply chain.
- H3: The advancement of information technology has a positive effect on sharing information in the supply chain.
- H4: Commitment impacts the sharing of information in the supply chain in a positive way.
- H5: Power has a markedly negative effect on information sharing in the supply chain.
- H6: Information sharing has a strong positive effect on the financial performance of the supply chain.
- H7: Information sharing has a high beneficial role to play in the non-financial performance of the supply chain.

On the basis of this statement and the hypotheses derived from it, we shall set out a simplified research model.

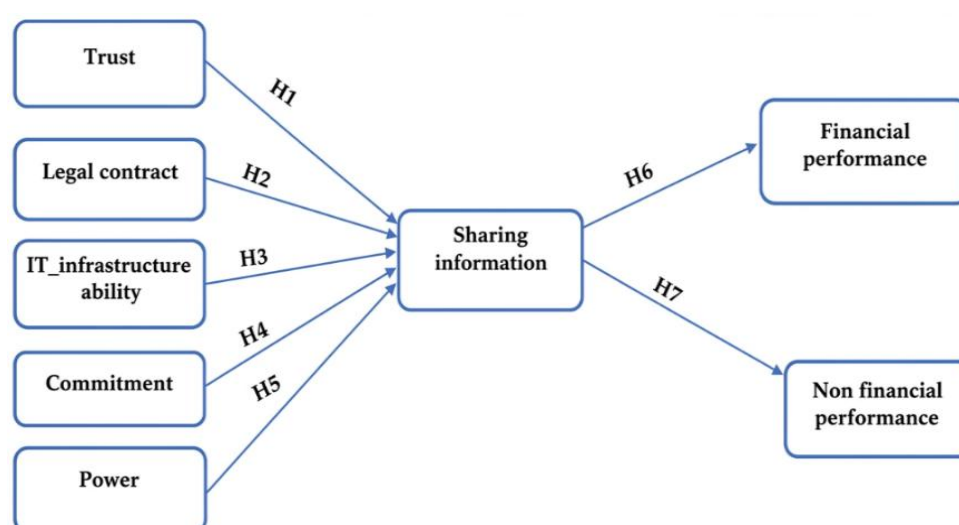


Figure 1 Simplified research model

In this direction, we initially conducted a Meta Analytic Review to cover the Information sharing aspects in Supply Chain Management. The outcomes of this preliminary stage serve as background to establish a starting point for the development of the Exploratory Analysis. The examination is conducted using a quantitative methodology along with the questionnaire data collection technique. In fact, our methodology seeks the selection of pre-existing measurement scales from the literature, the creation and organization of the questionnaire followed by its administration, the gathering of data to eventually use applications devoted to this subject (in our case we used IBM SPSS statistics version 28 and Smart PLS).

The remainder of the paper is structured as follows: section 2 presents the findings of the Meta Analytic Review. While section 3 is dedicated to describing our research process in a precise and structured way. In Section 4, a case study is conducted to test the proposed approach, then results are presented. While those results were analysed and discussed in section 5. Finally, in section 6, as a conclusion to our research, we want to develop a general assessment of our scientific added value, as well as the common threads for a future projection of this research.

2 Meta analytic review

Information sharing has been on the research agenda for several decades and continues to receive attention both from researchers and practitioners [1]. This interest is due to his role at the heart of the concept of the supply chain. It is the breadth of information exchanged in an interfirm relationship [2] that is also a fundamental element in managing the flow of information in the supply chain process [3]. Due to this interest, publications are multiplying, in this regard, we conducted a Meta Analytic Review to ensure the research rigor and replicability of the study and to encompass the diverse theoretical aspects surrounding our subject (The final sample consisted of 146 papers).

By combining the outcomes of the performed analyses, it is possible to provide insights into the main areas investigated by the literature on information sharing in supply chains, related risks, and opportunities.

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Figure 2, identified five major areas or aspects of information sharing in supply chains based on the analysis of the selected literature. First, a substantial body of research examines the impact of information sharing on supply chain performance. In total, 60 papers out of the 146 reviewed studies, representing nearly 41% of the sample, address this issue, highlighting the strong academic interest in understanding how information sharing contributes to supply chain effectiveness. Numerous empirical and theoretical studies [4-6] consistently demonstrate that information sharing is crucial for enhancing supply chain performance and fortifying connections among supply chain participants. Additionally, with 35 studies concentrating on the characteristics that affect the partners' willingness to participate in information exchange and the quality of the information shared, the drivers of information sharing represent a significant area of research, comprising almost 24% of the sample. These determinants are typically categorized into three principal groups: factors pertaining to individual psychology and behaviour, factors associated with information technology infrastructure and capabilities, and factors derived from Social Exchange Theory, encompassing trust, commitment, and reciprocity [7]. Thirdly, only fourteen papers investigate the challenges associated with the implementation of information sharing. There is less study that looks at the problems that come with information technology, but this stream generally looks at problems like information asymmetry, information distortion, opportunistic behaviour, and the bullwhip effect. Finally, there is a lot of talk in the literature on the many ways that firms share information. These approaches include many strategies, tactics, and processes used by corporations to enhance information exchange across supply chain participants.

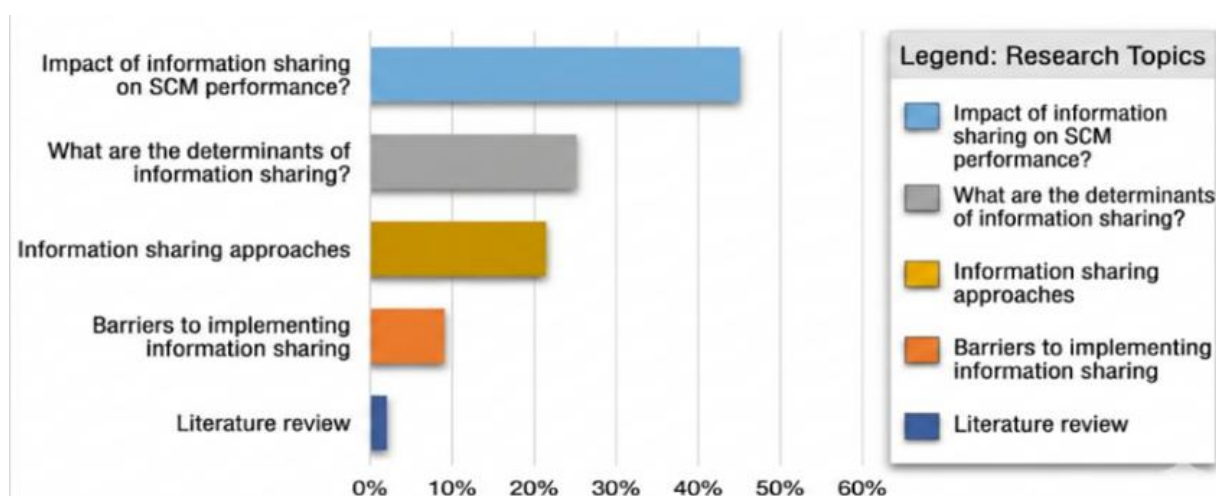


Figure 2 Distribution of articles by information sharing aspect

3 Methodology

Regarding methodological approach, we first conducted a Meta-Analytic Review. The findings of this first stage provide us the background we need to develop the theoretical model. Then, relevant variables were defined, and measurement scales were chosen. In a second step, we utilized a quantitative method using a questionnaire to collect data and to contrast finding with the reality of the Moroccan supply chain. This logic allows us to test our research model to affirm or refute the totality of our hypotheses,

3.1 The choice of measurement scales

Using the theoretical findings of the Meta-Analytic Review as a starting point, we were able to figure out what criteria are most crucial for sharing information and what performance measures are most relevant. The last phase included selecting appropriate and compatible measurement scales for our study's context. In this regard, the research conducted by [8] was used to define the Legal Contract dimension, while the scale developed by Doney and Cannon (1997) was employed to evaluate Trust. Concerning the Development of Information Technologies, the scale proposed by [9] was considered the most suitable, given its alignment with the objectives of the research. Commitment and Power were measured using established and widely validated scales, namely those developed by [10] for Commitment, and for power [11,12]. With respect to information sharing, we adopted the measurement scales proposed by [13,14], which have been extensively used in supply chain management research. Finally, performance was assessed using a combination of financial and non-financial indicators: financial performance was measured based on the scales developed by [12,13], whereas non-financial performance was evaluated using the measurement framework proposed by [15-17].

3.2 Sample characteristics

We have decided for the automotive sector. Our choice is attributed to a number of factors, namely (1) the development and growth of this sector in Morocco, (2) the large number of manufacturers who have recently decided to move to the

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kingdom, (3) the technology progress experienced by this sector requiring collaboration and communication among the various stakeholders in the chain to ensure a successful bet and increase profit.

Regarding the geographical location, we chose to work on the Tangier Automotive city located at Tangier. Thus, the final sample is 100 employees.

3.3 A quantitative investigation

There was a solid reason to choose a quantitative investigation. This scientifically-based, rigorous procedure is built on two main steps:

- We utilized SPSS to undertake an exploratory factor analysis (EFA) as the first step in reducing the amount of data. The approach allowed us to check the memory variables' internal consistency and look into the underlying structure of the measurement items. EFA was used to check the validity and reliability of the measuring scales, make sure they were unidimensional, and see whether the data samples were representative enough.
- Second, the research hypotheses were tested and the theoretical model was either validated or refuted through Confirmatory Factor Analysis (CFA) using Structural Equation Modelling (SEM). For this purpose, we opted for the SmartPLS software, which is particularly suitable for complex models and predictive-oriented research. SmartPLS enabled the assessment of both the measurement model and the structural model, providing robust estimates of relationships between latent constructs.

4 Results

This section presents the empirical results obtained from the analysis conducted in this study. The main objective is to examine the relationships between the determinants of information sharing and their impact on supply chain performance within the Moroccan automotive supply chain context. The findings presented in this section are based on statistical analyses conducted using the collected survey data. The results provide insights into the strength and significance of the relationships between the studied variables and help validate or reject the proposed research hypotheses. These results also offer an empirical foundation for the discussion and managerial implications presented in the following sections.

4.1 Exploratory factor analysis

Applying this procedure to our study allowed us to examine the correlations between the items of each variable to reduce them to a reduced number of factors. To accomplish this, we applied a Principal Component Analysis, which allowed us to delete the components that disturbed while still maintaining a coherent framework. In the end, 5 items were deleted, leaving 37 for the confirmatory analysis.

Table 1 shows, that the Kaiser-Meyer-Olkin index is (KMO) 0.858, _witch measure the sampling adequacy_, making the distribution homogeneous (Meritorious). Table 2 is rotated component matrix.

Table 1 PCA results

Measure / Test	Parameter	Value
Kaiser-Meyer-Olkin Measure	Sampling Adequacy	.858
Bartlett's Test of Sphericity	Approx. Chi-Square	4280.275
	Df(degrees of freedom)	666
	Sig.(p-value)	<.001

Table 2 Rotated component matrix

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Rotated Component Matrix							
Component Loadings for Identified Components (n=7)							
	1	2	3	4	5	6	7
A1					.756		
A2					.729		
A3					.782		
B1			.731				
B2		.443	.681				
B4			.668				
C1			.658				
C3			.640				
C4			.693				
D1	.837						
D2	.727						.482
D3	.707						.527
E1	.475					.646	
E2						.775	
E3	.475					.591	
F2			.585				
F3			.624				
G1	.970						
G2	.957						
G3	.971						
G4	.960						
G5	.974						
G6	.976						
G7	.962						
G8	.962						
H1				.0752			
H2				.780			
H3				.785			
H4				.774			
H5				.697			
I1		.672		.465			
I2		.752					
I3		.885					
I4		.786					
I5		.827					
I6		.621		.467			
I7		.691					
Extraction: Principal Component Analysis							
Rotation: Varimax with Kaiser Normalization (7 iterations).							

4.2 Confirmatory factor analysis

According to [18], structural equation modelling consists of two phases: Measurement and Structure. The measurement phase involves a confirmatory analysis to validate the items corresponding to the latent variables. On the other hand, the structural phase seeks to validate the hypotheses by analyzing the relationships of cause and effect between the variables that constitute the model.

4.2.1 Measurement model using SMART PLS

The measurement models for all concepts in our theoretical framework are assessed for appropriateness, reliability and validity.

Table 3 Reliability analysis and convergent validity analysis

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	Cronbach's Alpha	Composite Reliability	Average variance extracted(Validity)
IT	.993	.979	.853
Engagement	.857	.933	.874
Financial performance	.918	.938	.753
Information sharing	.800	.855	.500
Legal contract	.929	.826	.620
Non-Financial performance	.935	.947	.720
Power	.888	.930	.817
Trust	.773	.868	.687

To assess the reliability of our constructs, we will use Cronbach's Alpha and Composite Reliability (CR) (Table 3).

Regarding reliability (consistency), all coefficients exceed the reliability thresholds, as both Cronbach's Alpha and Composite Reliability exceed 0.7. Thus, the reliability of the different constructs of our model is good.

To assess validity, we will examine convergent and discriminant validity.

Convergent validity (Accuracy) has been established for all constructs, as the average variance of each item that makes up the construct exceeds the accepted threshold of 0.500. However, information sharing has a score of 0.500, making it still valid.

To validate the one-dimensionality of our measurement scales and the discriminant validity of our constructs, SMART PLS proposes several indices. we use The heterotrait-monotrait ratio of correlations (HTMT) witch (as mention Table 4) have a value equal to 1 with itself and less than 0.90 with the other variables. This means that we have a good Discriminant Validity.

Table 4 Discriminant validity analysis of variables using HTMT

	IT	Engagement	Financial performance	Information sharing	Legal contract	Non-financial performance	Power	Trust
IT	1							
Engagement	0.137	1						
Financial performance	0.106	0.649	1					
Information sharing	0.102	0.698	0.516	1				
Legal contract	0.786	0.094	0.086	0.095	1			
Non-financial performance	0.089	0.597	0.758	0.593	0.101	1		
Power	0.496	0.511	0.488	0.512	0.431	0.455	1	
Trust	0.088	0.642	0.468	0.779	0.135	0.375	0.485	1

4.2.2 Structural model using SMART PLS

The next step involves examining the structure of our model. This includes identifying any causal dependencies between our endogenous and exogenous variables. To accomplish this, we must first evaluate the quality of the model and then test the hypotheses to confirm or refute them.

Table 5 Analysis of the quality of the structural model

	R-square	R-square adjusted
Financial performance	0.216	0.208
Information sharing	0.521	0.495
Non-financial performance	0.285	0.277

Upon analysis of the R-square (showed in Table 5) results that are applied to our two output variables, financial and non-financial performance, it becomes apparent that:

Our model predicts 21% of the data in relation to financial performance.

Our model explains 28% of the data in relation to non-financial performance.

Table 6 provides a summary of our hypothesis testing based on the structural equation model:

Table 6 Summary of the hypothesis test

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	Hypothesis	T statistics	P values	Result
H1	Trust has a significantly positive impact on information sharing in the supply chain.	3.687	0.000	Accepted
H2	The legal contract positively affects sharing information in the supply chain.	0.468	0.460	Rejected
H3	The advancement of information technology has a positive effect on sharing information in the supply chain.	0.677	0.498	Rejected
H4	Commitment impacts the sharing of information in the supply chain in a positive way.	3.106	0.002	Accepted
H5	Power has a markedly negative effect on information sharing in the supply chain.	1.487	0.137	Rejected
H6	Information sharing has a positive effect on the financial performance of the supply chain.	3.760	0.000	Accepted
H7	Information sharing has a beneficial role to play in the non-financial performance of the supply chain.	4.570	0.000	Accepted

In conclusion, the impact of five input variables on the intermediate variable (information sharing) was investigated. According to the path coefficient analysis, two relationships were identified, namely the relationship between trust/commitment and information sharing. The same analysis revealed that the other three determinants did not explain the degree and frequency of information sharing in the supply chain.

Regarding the output variables (financial and non-financial performance), the analysis of the correlation coefficients showed a positive relationship between information sharing and these two variables throughout the supply chain.

We re-examine the design of our research model, (as visualized in Figure 3) stressing the contribution coefficients of each variable and emphasizing the relationships that have been validated and those that have failed.

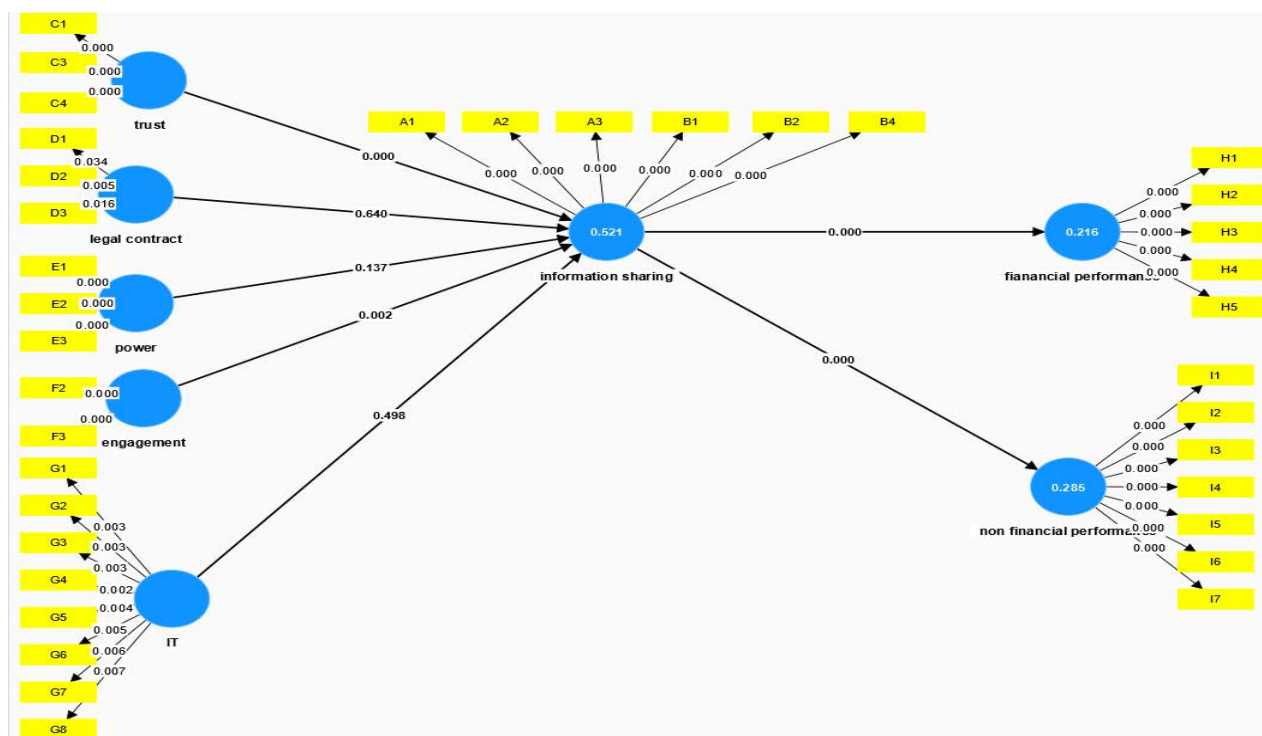


Figure 3 Modelling relationships using structural equations

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5 Discussion

The results obtained in this study provide important insights into the factors influencing information sharing and their impact on supply chain performance within the Moroccan automotive industry. Overall, the empirical findings confirm that collaborative relationships between supply chain partners play a critical role in facilitating effective information exchange. Thus the overall performance is positively impacted.

To make a comparison between results and literature review, and to justify the differences observed, we offer the following observations for each construct included in our research model.

Our results are discussed considering two central research questions.

5.1 To what extent do the drivers influence the exchange of information between the participants in the Supply Chain?

The literature review on this issue has uncovered numerous studies aiming to establish a linear relationship between various variables and information sharing in the supply chain. However, these studies typically focus on investigating one or more factors. In this context, we intend to discuss our results concerning each determinant separately, particularly in the case of our sub-hypotheses.

5.1.1 Trust has a significant positive impact on information sharing in the supply chain

Regarding this particular issue, the results show that there is a positive relationship between the fact that chain partners keep their promises and the degree and frequency of information exchange. This relationship is supported by a correlation coefficient of 3.687 with a significant p-value (0.000).

The analysis indicates that trust is the most significant determinant of information sharing. When supply chain partners develop strong mutual trust, they are more willing to exchange strategic and operational information. This result is consistent with previous studies in supply chain management literature, which highlight that trust reduces opportunistic behavior and encourages long-term cooperation between partners. [7] assert that trust is the paramount element influencing the extent of information sharing across enterprises. [20-25] demonstrate that trust is a big reason why individuals are willing to contribute, and they also illustrate how important trust is for getting better information. [8] assert that trust is an essential component of interpersonal acquaintance, subsequently influencing the intensity of collaborative efforts. Furthermore, do quantitative research within the context of information sharing to investigate the relationship between trust levels and the concept of social exchange [20]. We have decided to utilize information-sharing as our main way to measure consumer trust since it is such an important factor. The purpose of this approach is to help people who make decisions choose partners [21]. Moroccan auto workers said that trust between everyone in the chain is the most critical thing that makes it possible for information to flow.

5.1.2 The legal contract has a positive impact on information sharing in the supply chain

According to the hypothesis test, in the context of our study, the legal contract showed no effect on information sharing, contradicting the literature, which, on the contrary, confirms the benefits of this strategy.

From the employees' point of view, the presence of the governing structure is not sufficient to encourage them to share data among the stakeholders in the supply chain, and the legal contract will not succeed in protecting their benefits and rights.

5.1.3 The enhancement of information technologies has a positive influence on information sharing in the supply chain

A debate has emerged on the necessity of determining whether information and communication technologies (ICTs) will contribute to the process of knowledge sharing. This issue has increasingly caught the interest of researchers worldwide, given its vital impact on enhancing the speed and accuracy of exchange and its role in the coordination and decision-making process [22-24].

Thereby, Scuotto, Caputo, Villasalero, & Del Giudice (2017) support this viewpoint by asserting that information technology application is a useful way to assist partners share knowledge [25].

In our study of the automotive sector in Morocco, despite the availability and development of powerful software that facilitates this objective, its impact on the degree and frequency of information sharing remains statistically insignificant. This is supported by a T Statistic value of 0.677 and a p-value greater than 0.05, even with the identification of numerous very strong correlations.

This finding is surprising, but it seems that employees believe that the development of ICT has facilitated the exchange of information without necessarily affecting the willingness and extent information sharing. To put it another way, information technology is necessary for sharing but no longer serves as a driving force behind engagement (in the process of information sharing).

5.1.4 Engagement positively impacts information sharing in the supply chain

In the literature, engagement is often associated with trust or legal contracts, demonstrating its positive impact in combating opportunism and uncertainty [26-28].

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These findings are consistent with our results in the Moroccan context. Commitment has a positive and highly significant effect on the degree and willingness to share information among automobile supply chain stakeholders. Based on our sample, trust and engagement constitute a coherent set that has a motivational effect on chain actors to share information easily and frequently.

5.1.5 Power significantly has a negative impact on information sharing in the supply chain

Here we have found no causal relationship between power and the extent and frequency of information sharing, which is understandable as almost all elements of the sample believe that they do not exercise power in their relationship with their partners. This is reflected in the responses provided, which ranged from 'strongly disagree' to not agree. As most participants did not have this attitude, we could not identify any significant impact of this variable on the exchange of information.

5.2 How does this sharing affect the financial and non-financial performance of the chain in question?

Numerous studies delve into this question, even with the absence of a clear distinction between these two components in the existing literature.

The literature interrogates the relationship between information sharing and performance, often indirectly through the supply chain integration perspective. Several authors attempt to explore the impact of integration practices on performance, as seen in the works of Huang, [28-31].

In a different perspective, [24] suggest the integration of internal and external information is conducive to both reactive and proactive flexibility in the supply chain, resulting in high operational performance.

A considerable number of studies analyze the direct relationship between the impact of information sharing and supply chain performance. [22] prove that information sharing among chain partners through the use of RFID technology results in improved performance. Another study by [11] identifies two dimensions of information sharing: connectivity and willingness. Both dimensions affect operational performance. In addition, [20] find that information sharing has a significant impact on chain performance in terms of reducing total costs and increasing service quality [17,28,31].

The following is a description of our findings in terms of the order of our hypotheses:

5.2.1 Information sharing has a positive impact on financial performance

It is apparent that our model can successfully predict 21% of the data regarding financial performance when analyzing the R^2 results applied to this variable. This indicates that information sharing has a positive impact on financial performance, although this relationship is considered relatively weak. This is demonstrated by the correlation coefficient (path coefficient) of 3.760 with a significant p-value (less than 0.05).

5.2.2 Information sharing has a positive impact on non-financial performance

Our research model's confirmatory analysis showed that there is a causal link between sharing knowledge and performance that isn't related to money in the automotive supply chain. The R-squared, which is a measure of how well the regression is, shows the same relationship. Our model made up 28% of the total for measures that had nothing to do with money. This shows that sharing information has a positive influence on performance indicators other than financial ones, even when the rate seems low. The extremely high correlation coefficient (T: 4.570, Pv: 0.000) provides further proof that this is true.

This study underscores the significance of information sharing as a strategy to enhance performance and foster connections within the Moroccan automotive supply chain. Based on the statistics, it's evident that the ability to use technology and the ability to build relationships, including trust and commitment, have a big effect on how well partners can share information. Sharing information is a big part of both financial and non-financial success, and the fact that the two are linked in a good way indicates how important it is strategically. These results substantiate the proposed research methodology by validating established theoretical frameworks and provide robust empirical data pertinent to the Moroccan industrial context.

6 Conclusions

This study focused on information sharing across the Moroccan Automotive Supply chain, highlighting its impact on performance and pinpointing the primary determinants influencing its implementation. The study employs known theoretical frameworks and approved measuring scales to conduct a comprehensive and contextually relevant analysis. Results showed that Trust and Commitment have a significantly positive impact on information sharing. On the other hand, Power, the Legal contract and the Advancement of information technology does not markedly affect this one. Finally, the R-square Analysis showed that Information sharing has a positive effect on the overall performance of the supply chain. Even if the findings do provide us helpful theoretical and managerial insights, it's crucial to remember that there are certain limits. Culture, uncertainty, and opportunistic behavior were excluded from the research since they were deemed beyond the parameters of the selected factors. The results are not applicable to the whole Moroccan Automotive sector because of the restricted sample size and the geographical focus on the Tangier region. In addition, the findings are not generalizable to other businesses since

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the study examined just one. To address these limitations, further research should expand their sample to include more industrial sectors, while considering implementation challenges and information-sharing strategies as possible moderating factors. Qualitative study should complement quantitative evaluations to better explore practitioners' perceptions of information sharing in supply chains and the actual challenges it poses.

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Barriers to digital transformation in industrial, transport and logistics enterprises: empirical evidence from Kazakhstan

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44801 Bochum Süd, Germany, EU, kbota8788@gmail.com**Keywords:** digital transformation, digital readiness, industry, logistics, Kazakhstan.**Abstract:** Paper addresses the problem of systemic barriers to digital transformation, in logistics flows and supply chain management, which hinder the integration of digital technologies into material, information, and financial flows. The aim of the study is to empirically identify and analyze these barriers in industrial, transport, and logistics enterprises in Kazakhstan. The novelty of the research lies in specifying how barriers manifest in a transition economy and in demonstrating their impact on logistics flows and supply chain management. The empirical foundation of the research is a questionnaire survey conducted among 57 enterprises in the real sector of the economy, including industry, transport and logistics, construction, and information and communication technologies. The collected data were analyzed using descriptive statistical methods and interpreted within the broader context of industrial paradigm evolution, from Industry 4.0 toward the human-centric and sustainable Industry 5.0 model. The empirical material of the study reflects the cross-sectoral nature of digital transformation, encompassing production, logistics, management, and information processes within end-to-end digital ecosystems, as revealed through the survey of 57 enterprises in diverse industries. The results indicate that enterprise-level digitalization is still confined mainly to basic automation and fragmented adoption of digital tools, whereas integrated and intelligent solutions remain scarce and underdeveloped. Key barriers to digitalization emerge at the intersection of economic constraints, human capital limitations, organizational-managerial weaknesses, and technological challenges. The most prominent constraints include the high cost of digital solutions, persistent shortages of digital competencies among personnel, and insufficient strategic understanding of the potential benefits of digitalization.**1 Introduction**

Digital transformation in enterprises of the real sector is a crucial condition for enhancing competitiveness, sustainability, and adaptability amid ongoing structural changes in the global economy. The problem addressed in this study is that enterprises face significant obstacles in integrating digital technologies into material, information, and financial flows, which limits the development of logistics processes and supply chain management. The aim of the research is to empirically identify and analyze these barriers in industrial, transport, and logistics enterprises. The novelty of the study lies in specifying how barriers manifest in a transition economy and in demonstrating their impact on logistics flows and the formation of end-to-end digital ecosystems. Within industry, transport, and logistics, digital technologies are regarded as essential tools for optimizing processes, increasing transparency in supply chains, and reducing operational risks. However, empirical studies, including findings presented in this research, demonstrate that the actual level of digitalization of enterprises in Kazakhstan remains limited and does not correspond to the potential capabilities of the technologies being implemented.

Despite the proliferation of digitalization strategies and the formal adoption of quality management standards and information systems, digital solutions are still applied in fragmented ways used in fragments and mainly at the level of

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basic automation. This situation indicates the presence of persistent barriers that hinder the transition from digitalization of isolated functions to comprehensive digital transformation at the enterprise level. In a transitional these barriers acquire particular importance, as they intensify differences in digital maturity among enterprises and create a “digital asymmetry” across industry and logistics.

The purpose of this article is to empirically identify and systematically analyze barriers to the digitalization of enterprises in Kazakhstan, based on the results of a questionnaire survey of firms in the real sector of the economy. This work focuses on the empirical specification of barriers to digital transformation and their interpretation within the logic of a socio-technical approach and the transition from Industry 4.0 to Industry 5.0.

In the academic literature, barriers to digitalization have traditionally been examined primarily through the lens of technological constraints. More recent studies, however, emphasize that these obstacles are inherently complex and emerge at the intersection of technological, organizational-managerial, human capital, cultural, and institutional factors. In this context, increasing attention is devoted to the socio-technical approach, which conceptualizes digitalization as the outcome of interactions between technological systems and social structures.

Empirical studies reviewed in the literature indicate that the mere availability of digital technologies, infrastructure, and even formal strategic documents does not guarantee productive digitalization of production systems. In many countries, enterprises face situations in which digital solutions are implemented in a fragmented manner, insufficiently embedded in business processes, and fail to deliver the anticipated gains in efficiency and innovativeness [1,2]. This highlights the presence of systemic barriers that impede the transition from technological potential to genuine digital transformation.

This paper aims to provide an analytical systematization of the barriers to digitalization of industrial enterprises based on an interdisciplinary literature review and an empirical study of companies in Kazakhstan. The paper seeks to move beyond a narrow, technology-centric perspective of digitalization toward a comprehensive socio-technical analysis that accounts for the interdependencies between technologies, organizational structures, human capital, and the institutional environment.

2 Literature review

In academic literature, barriers to industrial digitalization have traditionally been analyzed mainly through the lens of technological constraints, such as insufficient automation, data deficiencies, system interoperability problems, and cybersecurity challenges [3,4]. More recent studies, however, emphasize that the most critical obstacles encompass not exclusively technological but also organizational, institutional, and socio-human factors [5-7].

Contemporary research pays particular attention to the gap between the technology-driven Industry 4.0 paradigm and the growing need to transition toward a more human-centric and sustainable model of industrial development, conceptualized within the Industry 5.0 framework [8,9]. In this context, barriers to digitalization are increasingly interpreted as manifestations of misalignment between technological solutions and the social and organizational conditions necessary for their effective implementation.

Despite the widespread diffusion of digital technologies and Industry 4.0 strategies, most industrial enterprises still encounter multi-level constraints that hinder comprehensive digital transformation. Recent research converges on the view that digitalization barriers are inherently complex and arising at the intersection of technological, organizational, human capital, cultural, and institutional factors [6,10-14]. Accordingly, this section presents a systematic classification of the key barriers to industrial digitalization.

Technological barriers

Technological barriers are traditionally considered the primary obstacles to digitalization, encompassing limitations in digital infrastructure, fragmentation of IT systems, low levels of automation, and interoperability problems between equipment and software. In many industrial enterprises, digital technologies are implemented in isolation, without integration into end-to-end production and managerial processes, which significantly diminishes their effectiveness [1,3].

Empirical studies indicate that even when data collection systems are in place, enterprises often fail to utilize the generated data for managerial decision-making and process optimization [1]. Similar conclusions are reported in studies on big data adoption in supply chains, where enterprises often encounter difficulties in data processing, interpretation, and transformation into actionable managerial knowledge [2].

Additional technological barriers include challenges related to cybersecurity, standardization, and the scalability of digital solutions. Small and medium-sized industrial enterprises (SMEs) are particularly vulnerable in this regard due to their limited financial and technical resources, a finding consistently supported by studies on SME digital readiness [4].

Organizational and managerial barriers

Organizational barriers to digitalization are closely associated with the absence of a clear digital strategy, insufficient support from top management, and weak coordination across organizational units. Numerous digital maturity models

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underscore that digital transformation necessitates systemic changes in governance and management practices rather than the mere adoption of new technologies [10].

In practice, digitalization initiatives are often implemented as isolated pilot projects that are not embedded within an overarching corporate strategy. This leads to the emergence of so-called “digital islands,” where innovations fail to scale and do not generate a substantial impact on productivity or competitiveness [6]. Moreover, rigid hierarchical management structures constrain the flexibility and adaptability required in the digital economy.

The literature also underscores a shortage of managerial competencies related to digital transformation, particularly at the middle-management level, which plays a pivotal role in translating strategic digital ambitions into operational implementation [11].

Human capital and competency barriers

One of the most critical barriers to industrial digitalization is the shortage of digital competencies among employees. Contemporary production systems require not only highly specialized technical skills but also basic digital competencies across a broad range of occupational groups [7,15]. Empirical studies demonstrate that insufficient levels of digital skills result in the inefficient use of implemented technologies and undermine the expected benefits of digitalization [7,16,17]. The study [18] identifies the skills and competencies employees need to possess for successful digital transformation of the company in the era of Industry 4.0. At the same time, many enterprises tend to focus on short-term needs for “hard” technical skills, while neglecting the development of adaptive, analytical, and interdisciplinary competencies.

An additional challenge is employee resistance to digital change, driven by fears of job displacement, increasing task complexity, and rising qualification requirements. These issues are particularly pronounced in traditional industrial sectors and reinforce the social barriers to digitalization [5].

Cultural and social barriers

Organizational culture plays a pivotal role in the success of digital transformation. Cultures oriented toward stability, hierarchy, and risk minimization often inhibit experimentation and the adoption of digital innovations [19]. Under such conditions, digitalization is frequently perceived as an externally imposed initiative rather than a source of organizational development.

Socio-technical research underscores that the lack of employee participation in digitalization processes reduces trust in and acceptance of new technologies [6]. In contrast, workplace innovation approaches demonstrate that employee involvement and the cultivation of a learning-oriented culture can help overcome social barriers and enhance the effectiveness of digital transformation initiatives.

Institutional and external barriers

The institutional environment also exerts a significant influence on industrial digitalization processes. Insufficient coordination between industrial, innovation, and education policies, as well as limited governmental support for digital initiatives, can slow down enterprise-level digital transformation [8].

Developing and transition economies face additional institutional barriers, including uneven development of digital infrastructure, shortages of qualified human resources, and constrained access to finance [20,21]. These factors intensify the divide between digital frontrunners and laggards and contribute to persistent digital asymmetries within industrial sectors.

3 Methodology

The empirical study employs a quantitative cross-sectional approach aimed at analyzing the current state of enterprise digitalization, the level of digital technology adoption, the development of personnel digital competencies, and the factors constraining digital transformation. This approach was chosen because it provides a reliable snapshot of the current state of digitalization and barriers across enterprises. It is particularly suitable for transition economies such as Kazakhstan, where digitalization develops unevenly across sectors. The quantitative design enables the collection of standardized data from a broad set of enterprises, allowing for statistical comparison between industries and the identification of systemic constraints. A structured questionnaire survey served as the primary method of data collection, consistent with established research practices in the field of enterprise digital readiness and digital maturity [4,10,11].

The empirical basis of the study consists of survey results from 57 enterprises operating in industry, transport, logistics, construction, and the information and communication technology sector. The selection of enterprises was guided by two criteria: (1) representation of key sectors relevant to digital transformation, and (2) availability of managerial and expert staff capable of providing informed assessments of digitalization practices. The cross-sectoral nature of the sample reflects the fact that digital transformation under modern conditions affects not only production processes but also logistics, supply chain management, information flows, and project activities, thereby forming end-to-end digital ecosystems [2,6,22].

The respondents were representatives of managerial and expert levels — enterprise heads, functional department managers, and specialists in digitalization, IT, and operational management — possessing relevant knowledge about the

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strategic, technological, and personnel aspects of organizational activity. This composition of respondents ensures the adequacy of assessments of the level of digitalization and the perception of barriers to digital transformation.

The data collection instrument was the author's structured questionnaire, comprising several logically interrelated blocks:

- general characteristics of the enterprise;
- innovation activity;
- the level of digitalization of functional areas;
- digital technologies employed;
- development of digital competencies of the staff.

The generated dataset comprises 124 variables, primarily quantitative in nature, supplemented by categorical indicators, thereby enabling a comprehensive analysis of enterprise digitalization characteristics. The data were processed using descriptive statistical methods, including analysis of frequency distributions and mean values. The interpretation of results was conducted within the framework of a socio-technical approach, allowing the identified barriers to be considered as elements of a unified system of enterprise digital transformation. The literature review demonstrates that barriers to the digitalization of industrial enterprises are complex and multi-level in nature, emerging at the intersection of technological, organizational-managerial, human capital, cultural, and institutional factors. Contemporary research emphasizes that the mere availability of digital technologies and infrastructure does not in itself ensure successful digital transformation if technological adoption is not accompanied by the development of human capital, the adaptation of managerial practices, and adequate institutional support. Within the socio-technical approach, these barriers are interpreted as manifestations of misalignment between technological capabilities and the social and organizational conditions necessary for their effective implementation.

The results of the empirical survey of Kazakhstani enterprises confirm the key conclusions of the literature review and further specify them within the national and sectoral context. The findings indicate that enterprise digitalization is predominantly confined to basic forms of automation and digital record-keeping, while the transition toward integrated and intelligent digital solutions is constrained by a combination of economic, human capital, and managerial limitations. Thus, the empirical results not only reproduce the typology of barriers identified in international studies but also demonstrate their specific manifestations in the context of a transition economy.

4 Results and discussion

This section presents a systematic analysis of digitalization barriers in Kazakhstani enterprises based on the results of the questionnaire survey. The analysis is conducted within the socio-technical framework and aims to identify the dominant constraints on digital transformation, their interrelationships, and their role in shaping the fragmented nature of digitalization. By linking insights from the literature with empirical evidence, the analysis goes beyond describing the level of digitalization to explain the underlying factors that hinder its deepening and transformation into a source of sustainable competitive advantage.

The survey results made it possible to identify and structure the key barriers impeding the digitalization of Kazakhstani industrial and related enterprises. The findings confirm that digitalization barriers are multifactorial in nature and consistent with the socio-technical logic, in which technological constraints are intertwined with human capital, managerial, and institutional conditions (see Table 1).

Table 1 Digitalization barriers as perceived by respondents

Barriers to digitalization*	Responses		Percent of Cases
	N	Percent	
High cost of digital technology implementation	28	19.6%	51.9%
Lack of understanding of the benefits of digitalization	20	14.0%	37.0%
Shortage of appropriately qualified personnel	20	14.0%	37.0%
Insufficient financial capacity to invest in digitalization	20	14.0%	37.0%
Insufficient digital infrastructure for digitalization	13	9.1%	24.1%
Barriers related to insufficient cybersecurity and data privacy	11	7.7%	20.4%
Barriers associated with digital standards, regulations and certifications	10	7.0%	18.5%
Insufficient interoperability between new digital solutions and existing management systems	9	6.3%	16.7%
Resistance of employees to organizational changes induced by digital transformation	5	3.5%	9.3%
Top management does not support digitalization initiatives within the enterprise	4	2.8%	7.4%
Insufficient availability of digital solution providers for the enterprise	3	2.1%	5.6%
Total	143	100.0%	264.8%

*Dichotomy group tabulated at value 1.

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The survey results indicate that the most significant barrier to digitalization is the high cost of implementing digital technologies, which was reported by more than half of the surveyed enterprises. This finding suggests that financial constraints remain a key limiting factor in digital transformation, particularly in the context of limited access to long-term financing and the high capital intensity of digital solutions.

The financial barrier is further reinforced by the lack of internal financial resources for investment in digitalization, reflecting not only resource scarcity but also constrained possibilities for capital reallocation within enterprises. Taken together, these results underscore that digitalization is perceived by firms as an investment-intensive and high-risk process, requiring substantial upfront expenditures amid uncertainty regarding economic returns.

A significant constraint on digitalization is also associated with the shortage of qualified personnel possessing the necessary digital competencies. A considerable share of respondents identified the lack of appropriately skilled specialists as a major barrier, corroborating prior research on the critical role of human capital in digital transformation processes. This finding reflects a structural gap between the technological requirements of the digital economy and the current level of workforce preparation, particularly in traditional industrial sectors. The absence of systematic programs for developing digital competencies further increases enterprises' dependence on external solution providers and limits their capacity for autonomous digital upgrading.

The analysis also reveals that digitalization barriers manifest not only at the resource level but also at the level of managerial decision-making. In particular, some respondents pointed to a lack of understanding of the benefits of digitalization, indicating insufficient integration of digital transformation into enterprise strategic planning.

In addition, cases were identified in which top management does not actively support digitalization initiatives, pointing to limited institutional engagement of leadership in digital change processes. Although this barrier is not widespread, its presence is of systemic importance, as managerial support largely determines the prioritization of digital projects and the allocation of resources.

Among technological constraints, respondents emphasized the lack of adequate digital infrastructure and the limited compatibility of new digital solutions with existing management systems. This reflects a situation common to many enterprises, where digitalization takes place within the context of outdated production and IT infrastructures, thereby complicating the integration of advanced solutions.

An additional technological barrier relates to insufficient levels of cybersecurity and data protection, as well as challenges associated with digital standards, regulations, and certification. These factors increase firms' caution toward digital technology adoption and generate institutional risks associated with digitalization.

The least frequently reported, yet still indicative, barriers include a shortage of digital solution providers and employee resistance to changes brought about by digital transformation. The relatively low incidence of reported resistance may be explained by the fact that in many enterprises' digitalization has not yet reached a stage of deep transformation of labor processes, where social tensions tend to become more pronounced. Overall, the findings point to an incomplete formation of a digitalization ecosystem encompassing competencies, financing, solution providers, and institutional support.

Table 2 shows a systematization of barriers to digitalization in enterprises in Kazakhstan based on empirical data and a literature review.

Table 2 Systematization of digitalization barriers in Kazakhstani enterprises: empirical evidence and literature review

Barrier Group	Specific Barriers (Survey Results)	Empirical Manifestations in the Study	Relevant Literature
Economic barriers	High costs of digital technology implementation; Lack of internal financial resources	Dominant barrier for more than half of enterprises; digitalization perceived as an investment-intensive and high-risk process with uncertain returns	Kagermann et al. (2013); Nick et al. (2019); Schumacher et al. (2020); Salamzadeh et al. (2024)
Human capital and competency barriers	Shortage of specialists with digital competencies; Insufficient digital skills among employees	Limited use of AI, analytics, and integrated systems; dependence on external solution providers; prevalence of “symbolic digitalization”	Steinlechner et al. (2021); Howaldt et al. (2016); Dessers et al. (2019); Müller (2020)
Organizational and managerial barriers	Lack of understanding of digitalization benefits; Limited top management support; Absence of a digital strategy	Digital initiatives implemented as isolated pilot projects; emergence of “digital islands” without scaling or strategic impact	Schumacher et al. (2020); Dessers et al. (2019); Salamzadeh et al. (2024)
Technological and infrastructure barriers	Insufficient digital infrastructure; Incompatibility of new solutions with legacy systems; Limited cybersecurity capabilities	Fragmented automation; low adoption of WMS, IoT, and AI; outdated IT landscapes hindering system integration	Qin et al. (2016); Nick et al. (2019); Chonsawat & Sopadang (2020); Queiroz & Telles (2018)

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Barrier Group	Specific Barriers (Survey Results)	Empirical Manifestations in the Study	Relevant Literature
Cultural and social barriers	Employee resistance to change; Low employee involvement in digitalization	Less frequently reported, but interpreted as latent; digitalization has not yet reached the stage of deep labor transformation	Howaldt et al. (2016); Kopp et al. (2016); Dessers et al. (2019)
Institutional and external barriers	Insufficient governmental support; Limited access to financing and digital solution providers	Reinforcement of digital asymmetries between enterprises; slower scaling of digital practices	Breque et al. (2021); Alzhanova & Kireyeva (2020); Kireyeva et al. (2022)

Taken together, the identified barriers point to the incomplete formation of a comprehensive digitalization ecosystem encompassing technology providers, a skilled workforce, financial instruments, and institutional support.

Overall, the results of the analysis indicate that the digitalization of Kazakhstani enterprises is constrained primarily by economic and human capital limitations, which are further compounded by technological and managerial barriers. The findings support the argument that digital transformation cannot be reduced to technological adoption alone and instead requires a systemic approach that integrates human capital development, managerial capabilities, and a supportive institutional environment.

4.1 Practical implications for enterprise management and industrial policy

Managerial implications for enterprises

The empirically observed fragmentation of digitalization highlights the need to manage digital initiatives as an integrated portfolio rather than as a collection of isolated pilot projects. In practical terms, this entails defining a target data and process architecture, prioritizing projects based on their impact on the value creation chain, and establishing a cross-functional governance body (e.g., a digital steering committee) involving representatives from production, logistics, finance, and human resources. Without such an approach, digital solutions are likely to continue generating “digital islands” rather than delivering systemic transformation.

Economic justification of digitalization through value-oriented metrics rather than ROI alone

The predominance of economic barriers points to a deficit of managerial tools for assessing the returns on digital investments. It is therefore recommended to complement traditional ROI calculations with value-oriented metrics, such as reductions in downtime and losses, improvements in demand and inventory forecasting accuracy, enhanced traceability, lower operational risks in supply chains, and improvements in the quality and speed of decision-making. This logic aligns digitalization more closely with the Industry 5.0 framework, in which value creation encompasses resilience and sustainability in addition to short-term financial performance.

Human capital strategy as the core of digital transformation

The shortage of digital competencies should be treated as a key second-order barrier: even when technologies are available, enterprises are unable to extract value without the necessary skills and a data-oriented culture. In practical terms, this implies: (a) conducting audits of digital competencies across employee groups; (b) implementing modular upskilling and reskilling programs for operational roles and middle management; (c) embedding on-the-job learning practices based on firm-specific use cases; and (d) developing internal “digital champions” who can reduce dependence on external consultants and facilitate knowledge diffusion within the organization.

Logistics as a priority area for digital impact

The low level of digital maturity in logistics and warehousing underscores the importance of selecting logistics as an effective “entry point” for data integration. In the short term, the greatest impact is often achieved through the implementation of WMS and basic traceability systems, the standardization of master data, and the introduction of scanners and sensors to enhance flow transparency, followed by the application of analytics for inventory management and planning. Such measures strengthen supply chain resilience, which represents a core objective of the Industry 5.0 paradigm.

4.2 Implications for industrial policy and development institutions

Reducing cost barriers through targeted financial instruments

Given that the cost of digitalization encompasses not only technology acquisition but also organizational transformation, blended policy instruments are likely to be most effective. These include co-financing schemes for digital implementation combined with support for training and consultancy services related to process reengineering. Of

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particular importance are concessional long-term financial instruments for small and medium-sized enterprises (SMEs) and firms with limited access to capital markets.

Competency-oriented policy as a systemic response to skills shortages

The study's findings underscore the need for institutionalized training and reskilling programs as a systemic response to human capital deficits. These may include sectoral competence centers, dual education schemes, short-term modular training for blue-collar occupations and middle management, and the standardization of digital skill profiles for industry and logistics. Crucially, educational programs should be closely linked to applied enterprise-level use cases; otherwise, their practical impact is likely to remain limited.

The digitalization ecosystem: clusters, demonstration platforms, and knowledge exchange

The fragmentation of digitalization and enterprises' dependence on external solution providers point to the need to institutionalize platforms for piloting and scaling digital solutions. These include testbeds, learning factories, and sectoral innovation hubs and labs. Such instruments reduce implementation risks for enterprises, accelerate the diffusion of best practices, and help overcome the "digitalization threshold" identified in the empirical analysis.

Data standards and interoperability as preconditions for scaling

Challenges related to system incompatibility and outdated IT landscapes highlight the need for policy support aimed at promoting data exchange standards and providing methodological guidance for system integration. At the policy level, this may include the development of reference architectures for key functional areas (such as logistics, quality management, and traceability) and certification mechanisms for digital solutions. Such measures can reduce uncertainty, enhance trust, and lower barriers to large-scale adoption.

Overall, the results confirm that barriers to enterprise digitalization in Kazakhstan should be interpreted as manifestations of a socio-technical misalignment: technologies are adopted more rapidly than the development of competencies, managerial maturity, and institutional support mechanisms. In this context, the transition from Industry 4.0 to Industry 5.0 implies a shift away from technological determinism toward a human-centric and sustainable model of digital development, in which the primary source of competitiveness lies in organizations' ability to integrate technologies into processes, develop human capital, and extract scalable value from data.

5 Conclusions

The aim of this study was to identify and analytically interpret the barriers to enterprise digitalization in Kazakhstan's real sector, based on empirical evidence and within the broader evolution of industrial paradigms from Industry 4.0 to Industry 5.0. The empirical analysis demonstrates that the digital transformation of the surveyed enterprises remains at an intermediate stage, characterized by basic automation, formal adoption of digital standards, and limited deployment of intelligent and integrated solutions.

The findings reveal that the dominant barriers to digitalization emerge at the intersection of economic, human capital, organizational-managerial, and technological factors. Economic constraints are reflected not only in the high costs of digital solutions but also in uncertainty regarding their returns under conditions of weak strategic integration. Shortages of digital competencies constitute a systemic constraint, reducing the effectiveness of implemented technologies and reproducing the fragmented nature of digital initiatives. Organizational and managerial barriers manifest in a limited understanding of the benefits of digitalization and insufficient leadership engagement, while technological and infrastructural constraints further amplify the risks associated with integrating and scaling digital solutions.

From a practical perspective, the results provide guidance for enterprises in designing comprehensive digital strategies, prioritizing investments, and embedding human capital development into transformation programs. They also highlight the need for industrial policy instruments that combine financial support with competency-oriented initiatives, thereby reducing systemic barriers to digitalization.

From a theoretical perspective, the study contributes to the literature on digital readiness and transformation barriers by offering an empirically grounded socio-technical interpretation of digitalization constraints in a transition economy. This perspective underscores that digital transformation cannot be reduced to technological adoption alone; rather, it requires a systemic approach integrating technology, human capital, managerial maturity, and institutional support.

Ultimately, the study advances the understanding of how socio-technical misalignments shape digitalization trajectories in emerging economies and provides a foundation for both academic inquiry and policy design aimed at fostering resilient, human-centric, and sustainable digital development in the era of Industry 5.0.

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Floating car data for urban traffic flow analysis: a case study of Olomouc

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Keywords: floating car data, traffic jam, traffic flow, HERE Traffic API, Olomouc.

Abstract: This paper examines the potential and limitations of floating car data for the spatiotemporal assessment of urban traffic congestion in a medium-sized city. Using traffic flow data obtained from the HERE Traffic API, the study analyses congestion patterns in Olomouc, Czechia, with a focus on daily trends, hourly variations, changes on selected specific days, and the spatial distribution of congestion across road segments. The data were collected at 15-minute intervals and aggregated to identify recurring traffic patterns and deviations associated with holidays, school-related changes, and pandemic restrictions. The results show that aggregated floating car data provide a robust basis for identifying recurrent congestion patterns, peak periods, and problematic road sections within the city. At the same time, the analysis demonstrates that single-day anomalies are often difficult to interpret without additional contextual information. The study confirms that floating car data are a useful source for medium-scale urban traffic monitoring, logistics planning, and comparative assessment of congestion, although their explanatory value is constrained by limited transparency in the underlying data generation process and by the absence of direct traffic counts.

1 Introduction

Urban traffic congestion remains a persistent problem in both large and medium-sized cities. It affects travel time, economic efficiency, environmental conditions, and the overall functioning of urban transport systems, including the management of passenger and freight flows, urban logistics, and supply chain operations dependent on reliable road transport. For this reason, detailed traffic monitoring and analysis are essential for transport planning, traffic management, and the development of intelligent transport systems. From the perspective of smart cities, contemporary traffic monitoring can also be understood as part of a broader sensor-based urban information infrastructure combining fixed sensors, mobile devices, and vehicle-based positioning systems.

A key aspect of transport-system analysis is the use of computer models that simulate traffic volumes and dynamics in relation to urban development [1-3]. Intelligent Transport Systems (ITS) represent one possible response to urban traffic problems. Their important component is the collection and analysis of real-time traffic data, which support both road users and transport system operators in decision-making. Such data can contribute to improved traffic management, lower congestion, and more efficient use of existing transport infrastructure.

With the growing number of vehicles, the need for more effective traffic management is increasing. Traffic congestion is a daily phenomenon affecting both large and medium-sized cities. Under conditions of limited urban infrastructure and resources, one of the most effective ways to understand and manage congestion is through traffic-data collection, analysis, and prediction. Two closely related challenges therefore arise: obtaining suitable traffic data and interpreting them correctly.

1.1 Conventional traffic data collection

Data on car traffic are collected using conventional (traditional) and non-conventional (modern) methods. From a conceptual point of view, conventional traffic data collection methods can be regarded as fixed sensor networks, in which

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traffic-related phenomena are monitored at predefined locations using dedicated sensing technologies. Conventional methods focus on the collection of data using sensors placed on or near the roadway. Thus, it is only the location near the relevant sensors that is always monitored. A range of sensing technologies is used in this context, including pneumatic tubes, piezoelectric sensors, magnetic detectors, infrared sensors, radar, and acoustic systems [4]. One recent trend is the use of image and video detection methods, and these are expected to have huge potential in the future due to the rapid development of artificial intelligence. Despite the development of automatic sensing technologies, manual or semi-manual traffic surveys are still used in many situations. Their main advantages are flexibility in site selection, temporal deployment, and the possibility of recording movement directions and vehicle types in detail. Such approaches are therefore still used in national traffic censuses [5] and in one-off surveys where long-term automated monitoring is not necessary or feasible. Overall, however, conventional methods are usually limited to selected road sections. Their wider deployment requires substantial financial and personnel resources. A fundamental limitation of such fixed sensor networks is their spatial rigidity, which restricts continuous monitoring across the whole urban area and motivates the use of complementary mobile sensing approaches such as floating car data.

1.2 Floating car data

In addition to conventional methods, crowdsourcing-based traffic data collection has become increasingly common. This approach relies on GPS devices installed in vehicles or on mobile phones whose users share their location. From these data, information on speed and direction can be derived from successive positions. The observed speed is then compared with the characteristics of the relevant road segment and refined using other sources, including historical records. This makes it possible to assess whether traffic on a given segment is flowing normally or is affected by congestion. The primary data may be relatively imprecise, but this is partly compensated for by the large number of devices involved. As a result, reliability tends to be lower on lightly used roads and higher on heavily used ones [7].

The main advantage of this approach lies in the widespread availability of data-collecting devices, which allows large-scale and near real-time traffic monitoring. Because no dedicated roadside infrastructure is required, acquisition costs may also be lower than in the case of conventional methods [7].

This approach makes it possible to build large and continuously updated traffic databases containing information on congestion, travel times, average speeds, and incidents. Widely used examples include Google Maps, Apple Maps, Waze, TomTom, Bing Maps, and HERE WeGo [3,7]. Most of these services are designed primarily for navigation, and access to their data is usually limited. Although application programming interfaces exist, they are often restricted in terms of spatial coverage, temporal access, or usage conditions.

One important source of FCD is HERE (formerly HERE Maps / HERE WeGo), which collects large volumes of location data from smartphones, portable navigation devices, in-vehicle systems, and other sensor-equipped platforms. These data are further refined using additional traffic-event information from a wide range of sources, including official portals, historical records, and other external inputs. The resulting database provides a robust basis for traffic services and is continuously processed through the HERE traffic engine.

HERE provides this data in XML or JSON formats via a REST API that allows a relatively high number of requests to the database after registration with a free account. The services provided by the HERE Traffic API include Traffic Incident Data, Traffic Map Overlays (Traffic Tiles), Traffic Flow Availability and, most importantly, the Traffic Flow Data service, which provides traffic information for individual user-defined road segments [8,9]. The service does not offer the complete road network for download, only the main road skeleton (major roads), but this is sufficient for most analyses.

1.3 Application of floating car data

Data provided by these platforms are used primarily in navigation applications to improve route selection and travel-time estimation. This practical orientation is also reflected in many published studies, which focus mainly on road safety [10], traffic light control [11,12], and network-analysis algorithms [12].

FCD can also be used for other purposes, especially traffic visualisation [12] and congestion analysis [13]. Existing studies emphasise the relative ease of data acquisition, the high spatial and temporal detail, and the usefulness of these data for identifying congestion and approximating traffic conditions [14,15].

During the COVID-19 pandemic, several studies used large-scale traffic and mobility data, including floating-car and probe-based sources, to assess changes in urban traffic flows under different levels of restrictions [16,17]. Related studies have also used proprietary congestion indicators to characterise broader traffic congestion patterns at city scale [18]. However, some authors caution that such indices do not allow straightforward interpretation of traffic improvement or deterioration and should not be used for simple inter-city comparison.

One relatively little used aspect of FCD is in the assessment of traffic situations (especially traffic congestion and traffic intensity) in cities, because this is not the primary purpose of FCD and, moreover, cities still use more traditional data sources for traffic assessment. Traditional data sources rarely provide continuous and spatially extensive information on congestion. Even comprehensive transport strategies often lack this perspective because such data are unavailable.

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This also applies to the Czech context, including the Sustainable Urban Mobility Plan of Olomouc [19,20]. At the same time, only a limited number of studies have addressed the use of FCD for detailed congestion analysis in specific urban settings [21-23].

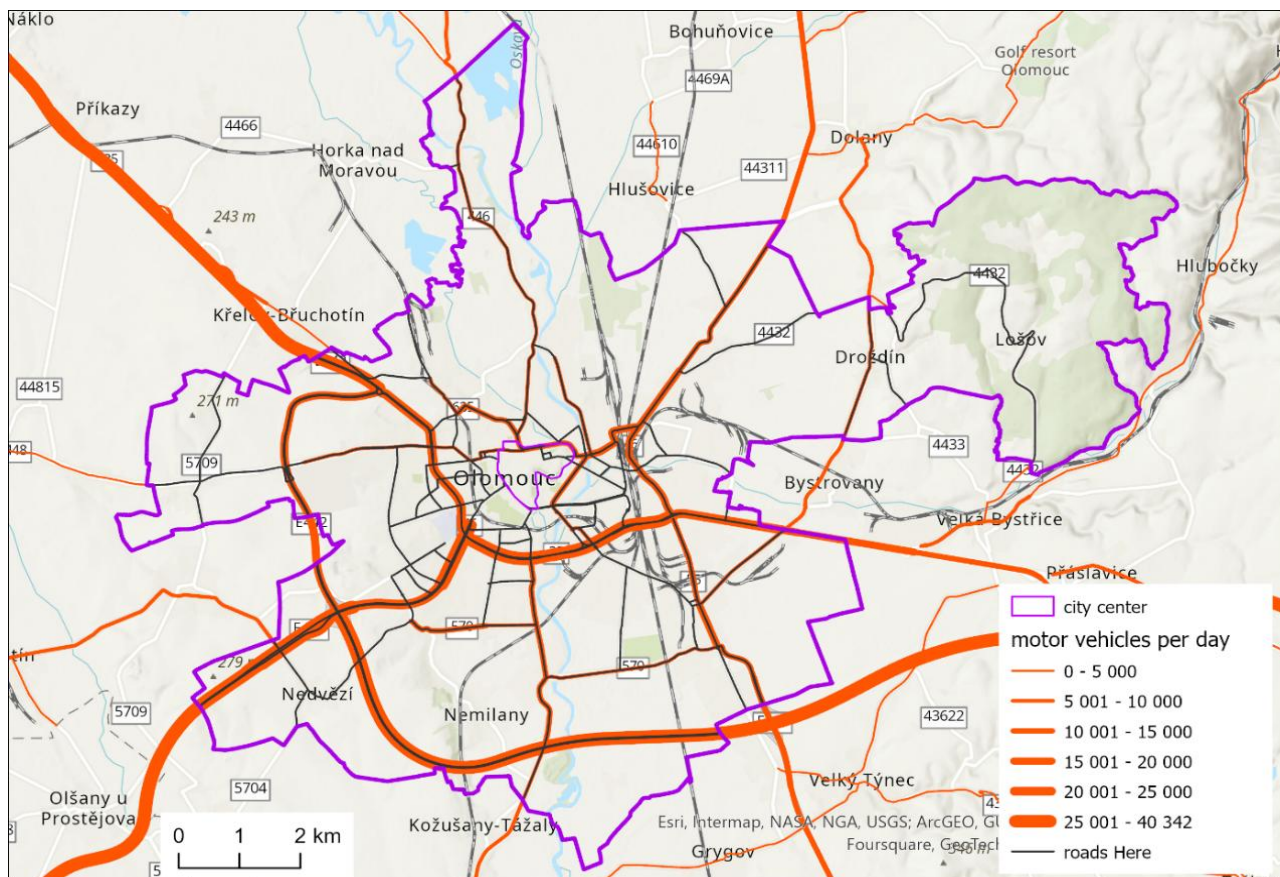
Recent research confirms that floating car data are increasingly used not only for navigation-oriented applications, but also for the spatiotemporal assessment of urban congestion patterns, traffic-flow modelling, and broader transport-planning tasks including urban logistics management and the optimisation of distribution flows [3,7,13]. At the same time, growing attention is being paid to the reliability, representativeness, and integration of FCD with complementary sensor sources, especially in urban environments where dense fixed-sensor networks are unavailable or spatially incomplete [24-29]. This is particularly relevant in medium-sized cities, where alternative sources of spatially continuous traffic information are often limited.

Against this background, this paper evaluates the potential and limitations of floating car data from the HERE Traffic API for the spatiotemporal assessment of urban traffic congestion in a medium-sized city. Olomouc is used as a case study to demonstrate how these data can be collected, stored, aggregated, and interpreted for the analysis of daily trends, hourly variations, specific-day effects, and spatial differences between road segments. The analysed period (2020-2021) is treated as a stress test of urban traffic behaviour under pandemic-related restrictions rather than as a representation of current traffic conditions. The main research question is whether HERE floating car data can serve as a meaningful source for assessing traffic intensity and congestion patterns in a medium-sized urban environment.

2 Data and methods

2.1 Study area

Olomouc (99,496 inhabitants in 2022; 103.33 km²) is the sixth largest city in Czechia and the administrative centre of the Olomouc Region. It represents a medium-sized urban centre with an important regional service, employment, and commuting function. The city is connected to the national motorway network, particularly via the D1/D46 and D35 corridors, and its road traffic is concentrated along the main tangential and radial routes (Figure 1). From the perspective of congestion analysis, these corridors form the key parts of the urban transport system and include both major transit links and heavily used inner-city sections. As Olomouc combines regional accessibility, daily commuting flows, and a relatively compact urban structure, it provides a suitable case study for assessing the potential of floating car data in a medium-sized city.



2.2 Data

The main data source was the HERE Traffic Flow dataset obtained through the HERE Traffic API. The data were collected automatically at 15-minute intervals and stored on a local database server for subsequent analysis. The area of interest was defined using a bounding box corresponding to the functional urban area of Olomouc. Data collection started in May 2020 and continued until the end of 2021.

The downloaded records were stored in a PostgreSQL/PostGIS database designed for time-series traffic data. Geometry and traffic attributes were stored separately, as the geometry of road sections remained unchanged over time.

A Python script was used to download traffic-flow records for all road segments within the study area at 15-minute intervals. The data were retrieved in JSON format and parsed into PostgreSQL tables. The database structure distinguished between time-varying traffic records and static road-segment geometry (Figure 2). For the purposes of this study, the key variables were measurement time, confidence, free-flow speed, speed, and jam factor. Jam factor was used as the main indicator of congestion intensity, while free-flow speed and confidence were used as supporting attributes for interpretation.

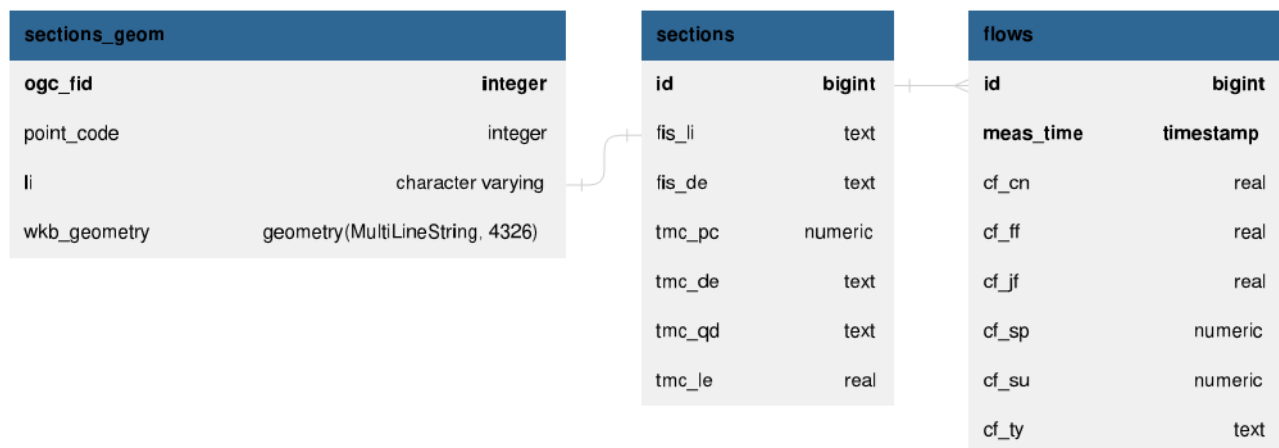


Figure 2 Data storage scheme

2.3 Methods

Data processing was carried out in the PostgreSQL/PostGIS environment using SQL queries, while aggregated outputs were further processed in Microsoft Excel. In addition to attribute data, the geometry of road sections was used to visualise spatial patterns. Because the HERE records are stored in UTC, timestamps were converted to local civil time, including daylight saving time where applicable. A key step in the workflow was the aggregation of 15-minute records into analytically meaningful time units. Because of occasional technical interruptions during the long download period, only complete and methodologically suitable time windows were selected for detailed analysis.

The analysis focused on representative time periods in which both long-term and short-term changes in congestion intensity could be observed. Time windows affected by obvious data failures or other distortions were excluded. For all analyses, the input data were aggregated into median hourly values for all road segments in the study area.

To demonstrate the analytical potential of HERE Traffic data, four model situations were selected: (i) daily congestion trends over a longer period (1 March 2021–30 June 2021), (ii) hourly congestion patterns during two selected weeks (17–23 August 2020 and 1–7 March 2021), (iii) changes on specific days compared with adjacent reference days (end of the school year, beginning of the school year, Christmas Eve, All Soul’s Day, Good Friday, and Easter Monday), and (iv) the spatial distribution of congestion across the urban road network. In the analysis of specific days, the difference between the medians of two consecutive days was evaluated, with one of them treated as specific.

For the spatial assessment, a typical summer week was selected to represent standard non-holiday traffic conditions. Median jam factor values were calculated for a typical working day and a typical weekend day. In addition, the morning peak period (7–8 a.m.) was analysed in more detail to capture the most pronounced congestion pattern within the daily cycle.

The spatial visualisation of results was prepared in ArcGIS Pro. As most road sections contained separate information for each traffic direction, line offsets were used to display parallel directional segments clearly.

3 Results

This section presents the main results of the spatiotemporal analysis of congestion patterns in Olomouc based on HERE Traffic data, focusing on daily trends, hourly variations, specific-day effects, and spatial differences across the road network.

3.1 Daily changes of the jam factor

Figure 3 shows the daily development of mean and median jam factor values in Olomouc between 1 March and 30 June 2021. Although the values are aggregated across all road segments and therefore represent a highly generalised measure of congestion intensity, the recurring weekly cycle is clearly visible, particularly in the regular decline during weekends. The time series also reflects the broader context of the COVID-19 pandemic, especially the gradual easing of movement restrictions at the end of April 2021. While median values remained relatively stable, mean values increased more visibly, suggesting that higher congestion levels appeared only on part of the road network and did not affect the city uniformly. A short-term spike can be observed on 26–27 April 2021, which may be related to the partial return of pupils to schools and the re-opening of selected services. However, this effect was temporary and was not followed by a lasting increase in congestion intensity.

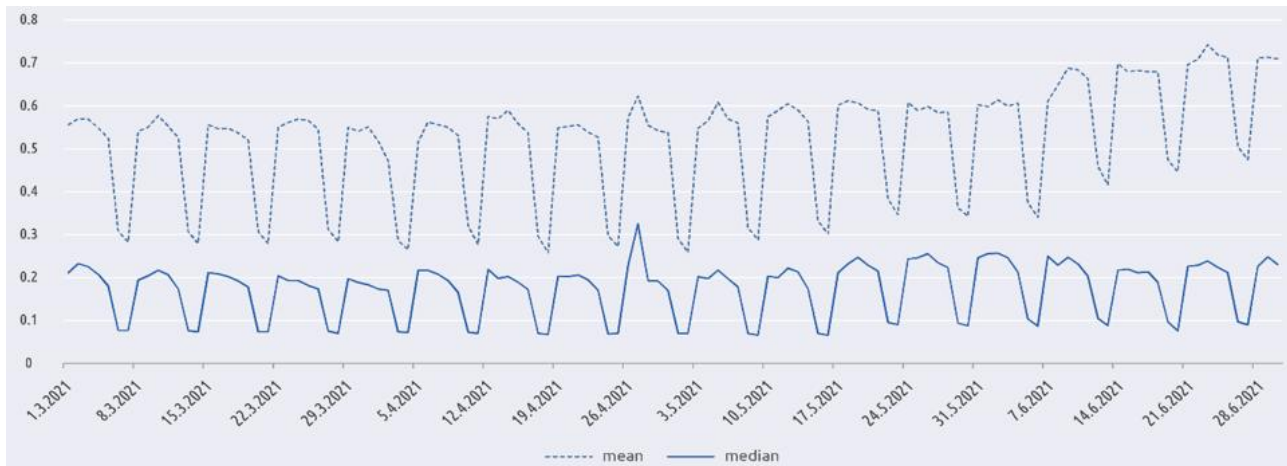


Figure 3 Time series of mean and median jam factor values between 1 March and 30 June 2021

3.2 Hourly variations in the jam factor

Because of the detailed timestamps, HERE Traffic data are also suitable for analysing intra-week congestion patterns in greater detail. In the next step, median hourly jam factor values were evaluated over a whole week and visualised as a heatmap (Figure 4). For comparison, a “normal” week (17–23 August 2020) and a “specific” week affected by COVID-19 restrictions (1–7 March 2021) were selected.

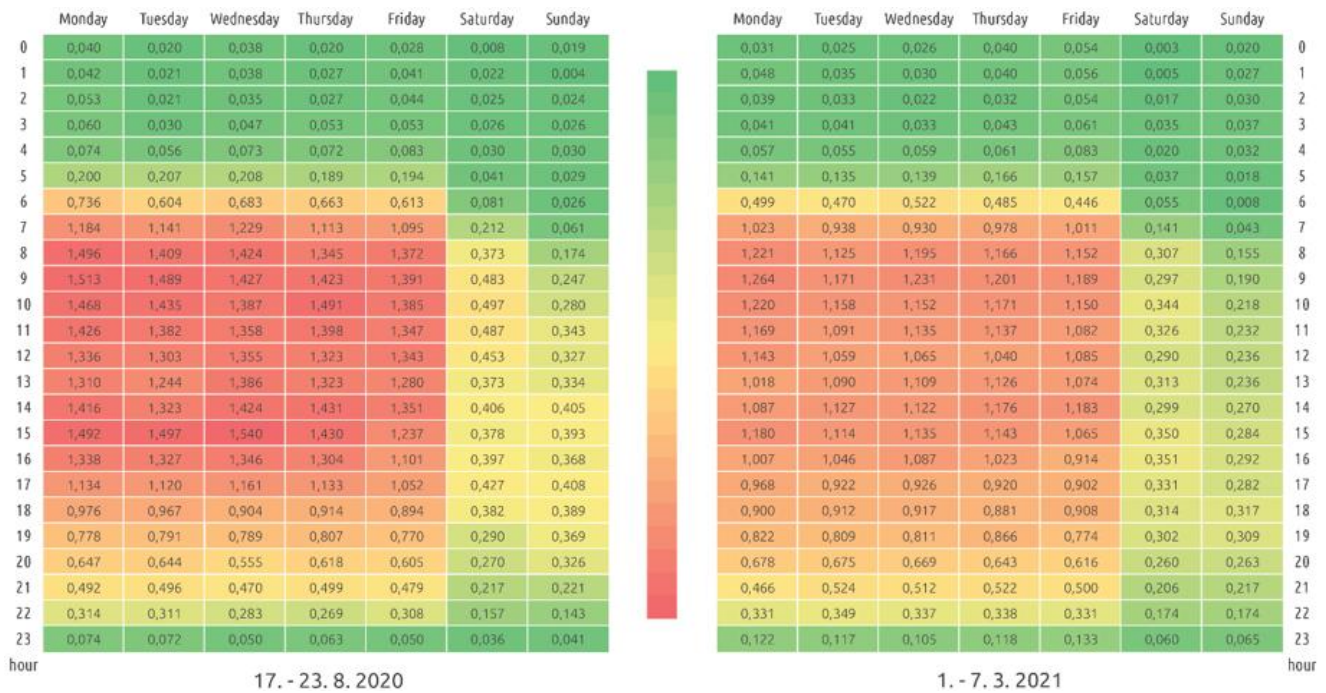


Figure 4 Matrix of daily-hour jam factor values during the regular week (left) and atypical week with the COVID-19 restrictions (right)

In the normal week, a recurring daily pattern can be observed on all working days. Jam factor values remain very low at night, begin to increase between 4 and 5 a.m., and rise further during the morning peak between 7 and 9 a.m. Elevated values persist until midday and culminate again in the afternoon, especially around 3 p.m. From late afternoon onwards, congestion intensity gradually declines. A slight decrease can be observed towards the end of the working week, particularly on Thursday and Friday, when peak values are lower than on the preceding days.

The contrast between weekdays and weekends is pronounced. On Saturday, higher jam factor values are concentrated mainly in the first half of the day, while on Sunday they shift more towards the afternoon. Compared with weekdays, however, weekend congestion levels remain substantially lower.

Compared with the normal week, the week affected by COVID-19 restrictions shows an overall reduction in congestion intensity, especially on working days. The general daily pattern remains similar, but jam factor values are consistently lower and the late-week decline is less pronounced. Weekend values are also lower, although the contrast with a normal weekend is smaller than in the case of weekdays. These differences are consistent with reduced commuting and lower overall mobility during the period of pandemic-related restrictions.

3.3 Jam factor changes on specific days

In the next part of the analysis, selected specific days were examined to assess whether HERE Traffic data capture noticeable deviations from usual traffic patterns. The evaluation focused on the end of the school year, the first day of school after the summer holidays, the Christmas period, All Soul's Day, Good Friday, and Easter Monday.

At the end of the school year, a decrease in mobility might be expected due to reduced school commuting, especially trips made by parents taking children to school. However, it can be seen from Figure 5 that the expected decrease in the 7 a.m. morning commute is not observed. In contrast, a slight increase is observed in the afternoon. This may reflect the beginning of the holiday season and a slight increase in leisure-related mobility. Overall, however, the observed differences are very small.

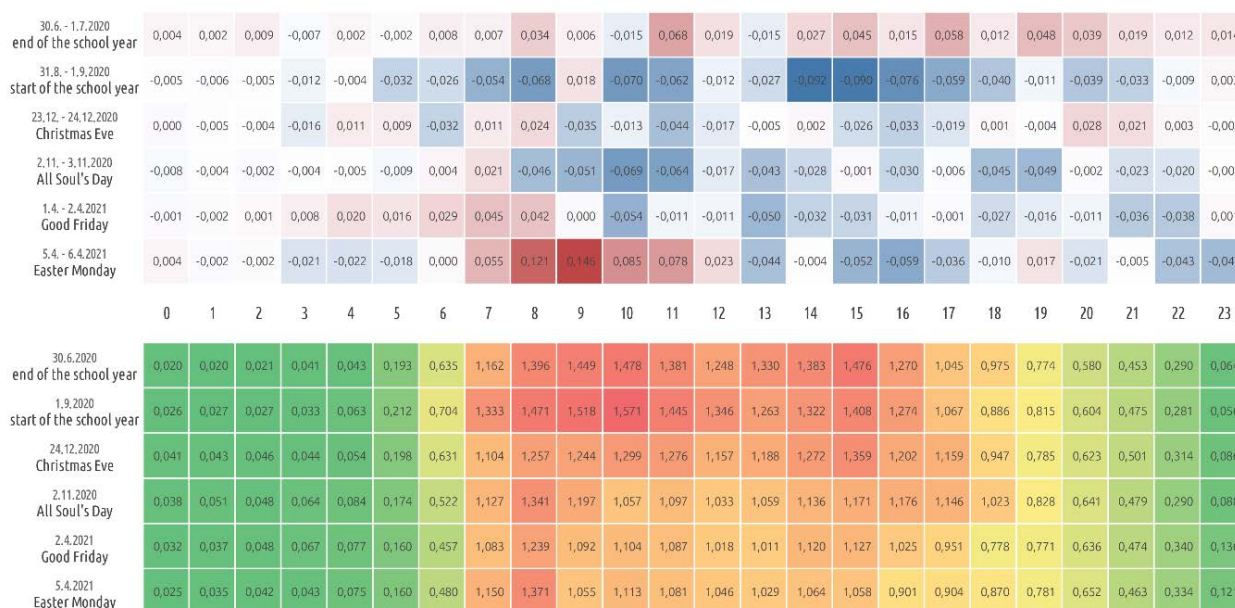


Figure 5 Difference in the median value of jam factor on two consecutive days (top);
absolute median value of jam factor on a specific day (bottom)

An opposite effect was expected on the first day of school after the summer holidays, when traffic intensity should increase at times associated with pupils' journeys to school. The beginning of the school year coincided with the early stage of the autumn COVID-19 wave, although no mobility restrictions had yet been introduced. Therefore, the observed decrease in intensity is contrary to expectations and there is no clear interpretation for it. The Christmas period is typically associated with marked changes in mobility patterns compared to normal days. They are also influenced by changes in the opening hours of shops, restaurants, sports and entertainment facilities, and cultural events. The Christmas period is also characterised by frequent visits to family members and friends, which may further affect traffic patterns. In this case, we observe a slight decrease in intensity compared to 23 December (Wednesday), which corresponds to the expected behaviour. However, we would expect a more significant decrease, especially in the evening hours.

All Soul's Day in 2020 fell on 2 November (Monday) and may be considered specific because of increased visits to cemeteries in the late afternoon. To make a comparison with another weekday, a difference was observed on 3 November. A decrease in traffic intensity is observed, but the highest values still occur in the morning, which is not consistent with the expected pattern. In terms of absolute intensity measures, the jam factor is highest at 8 a.m., then holds fairly constant through the day until 5 p.m. Good Friday (2 April 2021) is a public holiday, so a decrease in traffic would be expected compared to Thursday. At the same time, people may use the day off for recreation and visits, so no clear expectations regarding the direction of change can be set. Compared with Thursday, a slight increase is observed in the morning, while afternoon and evening differences are negative but very small. In terms of the absolute value of the jam factor, the intensity was highest at 8 a.m. and decreased thereafter.

Although Easter Monday is traditionally associated in Czechia with visits to relatives and friends, the data show a marked increase in intensity on the following Tuesday (6 April 2021), especially in the morning hours. It can be concluded that despite the visits mentioned, Easter Monday is much quieter in terms of traffic than the following normal working day. The absolute values of the intensity on Easter Monday indicate increased activity at 8 a.m., which is in line with the tradition of morning visits.

3.4 Spatial distribution of the jam factor

The final analytical output is a spatial assessment of congestion intensity across individual road segments in the study area. This output was prepared by linking jam factor values with the spatial data of road segments in the city. Each segment was assigned an aggregated value expressing the median jam factor for the selected period. The assessment was performed for a typical working day, a typical weekend day, and the morning peak period on a working day.

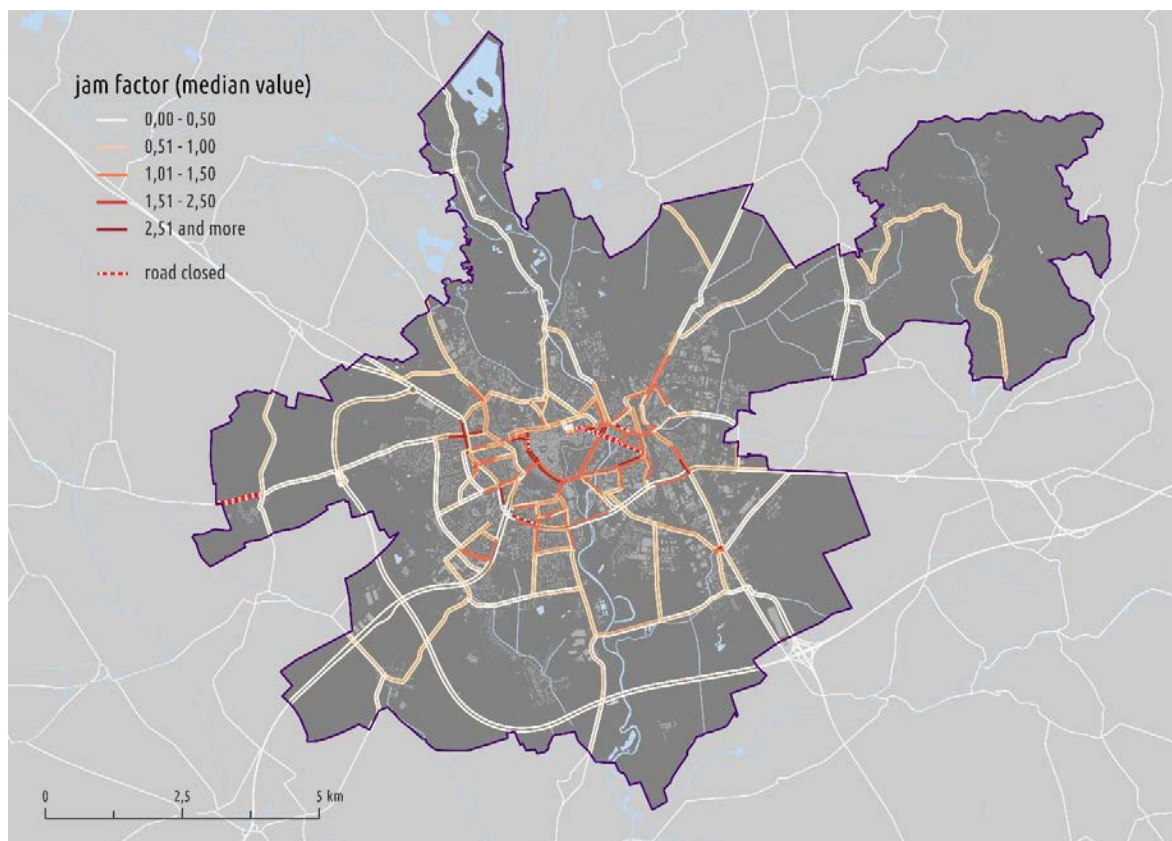


Figure 6 Jam factor on a typical working day
(median values for road segments during 17-21 August 2020)

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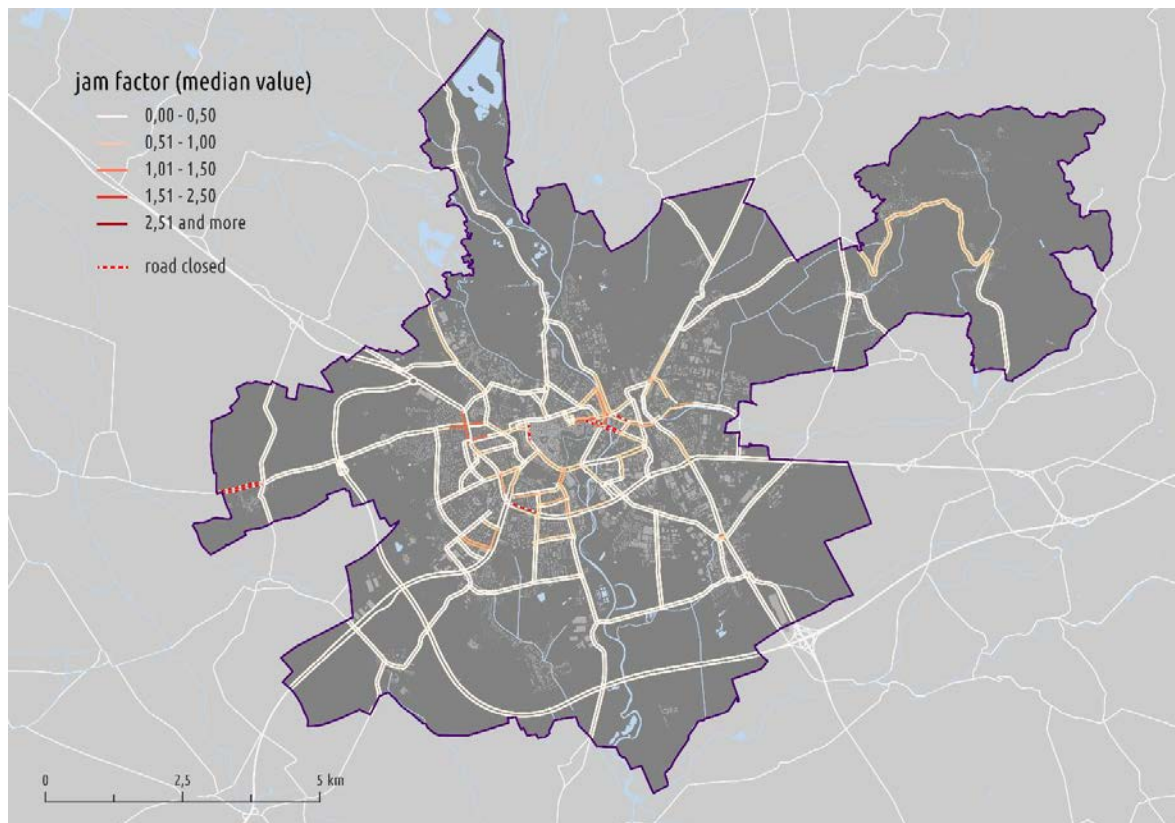


Figure 7 Jam factor during the weekend
(median values for road segments during 22-23 August 2020)

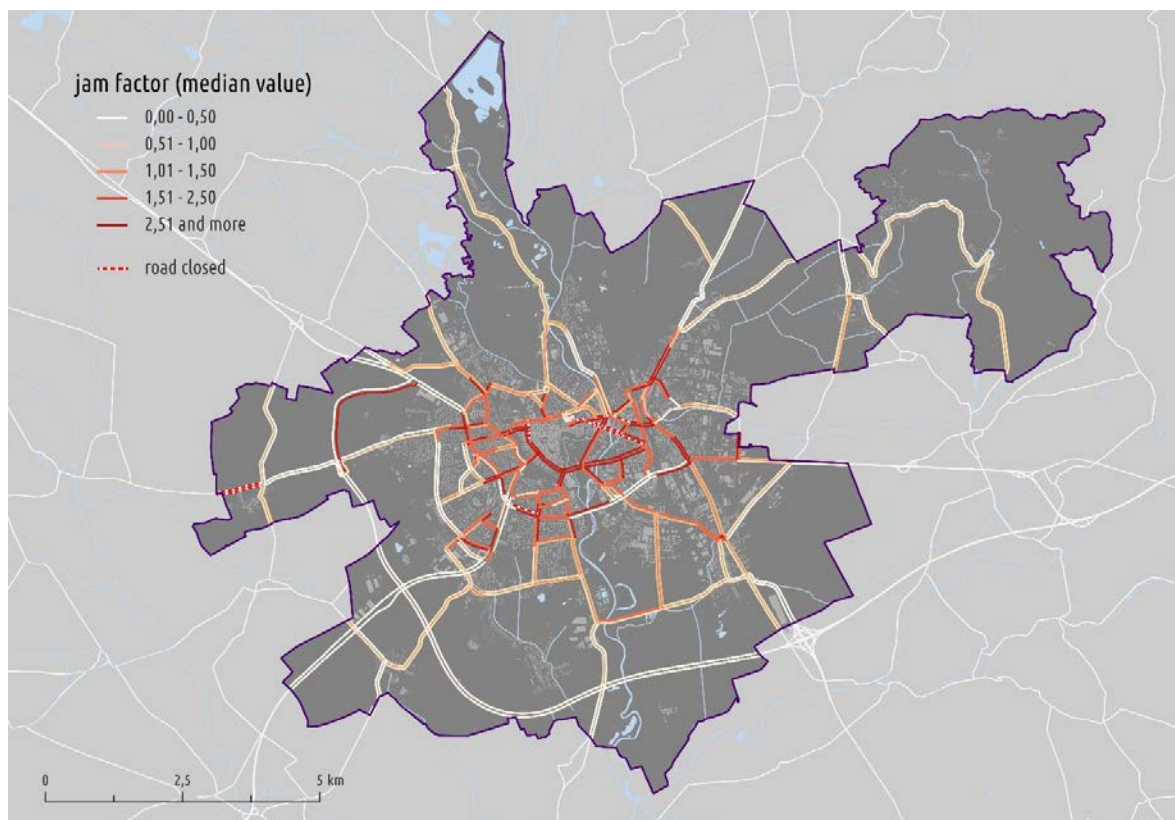


Figure 8 Jam factor on the morning peak on a typical working day
(median values for road segments during 17-21 August 2020, 7-8 a.m.)

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First, the spatial pattern of congestion on a typical working day was compared with that at the weekend. Although the median values for all hours of all weekdays were aggregated by road segment, Figure 6 shows a clear spatial pattern of congestion in Olomouc. Higher jam factor values are concentrated in the inner parts of the city. Tr. Svobody, which bypasses the historical centre, stands out as one of the most congested sections. Kosmonautů Street, linking the railway station with the city centre, shows a similarly high congestion intensity. These sections correspond well to everyday urban traffic experience. Importantly, the most congested sections are not necessarily those with the highest traffic flows, but rather local road segments where traffic flow is repeatedly slowed down. Higher jam factor values are also visible on some main outbound routes, particularly on the I/35 road towards the north of the city. The adjacent districts of Pavlovičky, Bělidla, and Chválkovice can therefore be regarded as problematic in terms of the regular occurrence of congestion. The city bypass carries high traffic flows as well, but congestion appears there less frequently than on the above-mentioned urban sections.

The weekend visualisation (Figure 7) shows substantially lower jam factor values across most parts of the city than on weekdays. The strong weekday–weekend contrast was already evident in Figure 4, but the spatial view confirms that no major part of the city experiences pronounced weekend congestion. Higher values remain visible mainly in the city centre, but even there they are markedly lower than on working days.

In addition, traffic conditions were examined in more detail for the morning peak on a typical working day in order to capture the most pronounced congestion pattern within the daily cycle. Based on previous findings on traffic behaviour in Olomouc [23], the interval from 7 to 8 a.m. was selected as the main peak period. The spatial visualisation is presented in Figure 8. Compared with the general weekday pattern, the morning peak confirms the concentration of congestion on the main radial and tangential routes, especially in the inner parts of the city and on key links connecting the centre with surrounding districts. No fundamentally different spatial pattern was observed, but the morning peak highlights the road sections where congestion intensity is most pronounced.

4 Discussion

During the evaluation period, traffic in Olomouc was also affected by the closure of some roads, which resulted in increased or decreased congestion intensity in some of the analysed sections. This was mainly due to the implementation of flood protection measures on the Morava River associated with the reconstruction of bridges on Komenského Street and Masaryk Avenue. These construction works required the diversion of traffic from closed roads to other routes. However, given the longer duration of these closures, the observed traffic patterns may still be regarded as relatively stable, as most drivers had already adapted to the changed traffic conditions. The affected sections are indicated in the map outputs.

The main limitation of the presented analyses lies in the nature of the input data. The HERE Traffic API technical documentation [8] provides only limited information on how the traffic indicators are generated. Despite the broad applicability of Floating Car Data (FCD) for traffic and infrastructure monitoring, their indirect nature and variable spatial coverage may limit the accuracy of derived traffic-state indicators when used in isolation. Recent review studies highlight that these limitations are increasingly addressed through the integration of FCD with heterogeneous sensor-based data sources, framing FCD as one component of broader traffic-sensing and data-fusion ecosystems rather than a standalone solution [3]. Recent research has shown that integrating FCD with complementary sensor sources can improve the robustness and interpretability of traffic and infrastructure measurements. For example, fusing commercial FCD with Bluetooth sensor data has been demonstrated to improve average link speed estimates and provide more consistent traffic performance assessment across urban corridors compared with single-source methods alone [25]. A similar direction is represented by recent multisource traffic-state estimation approaches, which show that combining heterogeneous sensor streams can improve the quality and stability of urban traffic assessment [27]. Moreover, the use of FCD has been extended beyond conventional traffic metrics, for example to the assessment of pavement roughness for maintenance planning, which illustrates the wider potential of probe-based data but also emphasises the need for validation against high-quality reference measurements [26].

A related issue is the substantial level of uncertainty inherent in the analysed data, which is not always sufficiently acknowledged in studies using FCD. Some important characteristics remain unknown, such as the number of vehicles contributing to the indicator on a given road segment and whether the number of probe vehicles is sufficient on marginal road sections for the published values to be considered representative. At the same time, previous studies have shown that acceptable estimates of aggregated traffic variables, especially speed-based indicators, can still be obtained even at relatively low probe-vehicle penetration rates; for example, [28] demonstrated that penetration levels of around 5% may already provide reasonable estimation quality for urban road segments when appropriate quality–penetration relationships are applied. Similar limitations are mentioned by [24], who identify the inability to validate data reliability as one of the main weaknesses of this type of data source. The automated processing by the HERE engine probably addresses reliability to some extent, as it provides a “confidence” attribute, but the user is not given sufficient information to evaluate how this reliability is derived. For these reasons, the data are not suitable for real-time operational traffic control tasks that require precise vehicle counts and very high temporal responsiveness. However, the analyses confirm that, when

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aggregated over longer time periods, Floating Car Data provide a robust basis for strategic and tactical traffic planning, including the identification of congestion patterns and travel time reliability assessment. The interpretability of these data could be further improved by systematic comparison with observations from independent urban sensor networks, which may help to refine the evaluation of congestion patterns and support local validation of derived traffic indicators. This limitation is particularly important in medium-sized cities, where congestion patterns are often shaped by a combination of recurrent daily commuting, local bottlenecks, and temporary traffic disturbances, and where the interpretation of probe-based indicators therefore requires careful contextualisation.

Another weakness is the partial spatial coverage of the data. Although the dataset covers a very large area, including all European countries, representativeness is likely to be highest on the backbone network of major roads with sufficient traffic flows. However, the rules according to which road segments are included are not known, and in some cities data may be missing for roads that are important for local traffic conditions.

The interpretation of jam factor values is also problematic. For the user, jam factor is essentially a numerical index whose absolute magnitude is difficult to translate into a clear verbal interpretation. Due to the aggregation of values over time or space, the observed differences within a day are often rather small. It is therefore difficult to determine with confidence whether a particular absolute difference between two jam factor values should be regarded as significant. This problem is particularly evident in the assessment of changes on selected specific days. The observed differences are often very small, and it is not possible to determine reliably whether they reflect the consequences of a specific event, natural variability, or other external influences such as weather-related changes in traffic behaviour. For this reason, the data are less suitable for detailed interpretation of small differences between selected individual days, especially where no strong external context is available.

At the same time, the results show that basic temporal and spatial traffic-flow trends can be captured by these data, especially over the long term. This is evident, for example, when comparing usual traffic conditions with the patterns observed during the COVID-19 restrictions, and similar conclusions are reported by [16]. Owing to the possibility of collecting data at 15-minute intervals over a long period of time, it is also possible to identify with reasonable precision the locations where the most pronounced congestion occurs, which is consistent with findings reported by [15]. In the study area, the most problematic locations correspond both to the general awareness of recurrent congestion in the city and to the conclusions of the Sustainable Mobility Plan [19], where problematic road sections were also identified through field survey. A major advantage of HERE Traffic data is that such assessment can be carried out in a uniform way over long time periods and across an almost unlimited spatial extent. In this respect, the present study is consistent with recent work showing that floating-car and probe-based data are particularly useful for identifying stable congestion structures and recurrent bottlenecks, whereas their explanatory value is lower for short-term deviations without additional contextual evidence [26,30].

In Czechia, where the most commonly available official traffic data are still based primarily on vehicle counts from the national Transport Census [5], HERE Traffic data represent a particularly valuable additional source of information. Beyond traffic engineering, such data have direct relevance for logistics operations, distribution planning, and supply chain management, where knowledge of recurring congestion patterns and freight flow conditions on specific road segments is essential. They can be used alongside existing traffic surveys, traffic models, and data from conventional sensors, which usually monitor only a limited number of locations or selected time periods. In this respect, HERE Traffic data offer an important advantage, as they can be analysed for almost any time frame without major limitations in spatial extent. At the same time, they should always be interpreted critically and in relation to other official or locally validated data sources.

A specific contribution of this study lies in showing that long-term aggregation of floating car data can reveal stable spatial and temporal structures of congestion in a medium-sized city, whereas short-term anomalies remain more difficult to interpret reliably. In this sense, the study contributes not only to the empirical understanding of traffic congestion in Olomouc, but also to the broader discussion on the applicability of commercial floating car data in urban traffic-flow assessment outside large metropolitan areas.

5 Conclusions

This paper evaluated the potential and limitations of floating car data from the HERE Traffic API for the spatiotemporal assessment of urban traffic congestion in a medium-sized city, using Olomouc as a case study. The analyses showed that long-term aggregation of jam factor values makes it possible to identify stable daily, weekly, and spatial patterns of congestion and to highlight problematic road sections and peak periods within the urban transport system. In this respect, the results confirmed that floating car data can capture the main structural features of urban traffic flows and provide a useful basis for the comparative assessment of congestion conditions across the road network.

At the same time, the study also showed that the interpretation of short-term anomalies observed on selected specific days is less straightforward and depends much more strongly on contextual knowledge. Small differences in aggregated jam factor values cannot always be interpreted reliably without additional information on the underlying causes of traffic

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changes. This applies in particular to situations where multiple external influences may overlap, such as holidays, weather conditions, temporary restrictions, or changes in daily routines.

The main contribution of the study therefore lies not only in the empirical assessment of congestion patterns in Olomouc, but also in demonstrating the analytical possibilities and limits of floating car data in a medium-sized city. From a practical perspective, these data can support transport planning, traffic management, urban logistics coordination, and the identification of bottlenecks affecting the flow of goods and passengers in situations where conventional traffic surveys do not provide sufficient spatial or temporal detail. Their main advantage lies in the possibility of repeated and spatially extensive monitoring of traffic conditions over long time periods, which is difficult to achieve using conventional field surveys alone.

At the same time, the study confirms that HERE Traffic data should not be interpreted as a direct substitute for conventional traffic counts or other validated sensor-based measurements. Rather, they should be understood as a valuable complementary source that is particularly suitable for the identification of long-term congestion patterns and spatial differences in traffic conditions. Future research should therefore focus on the combined use of floating car data with other reference sources, on the validation of congestion indicators under different urban traffic conditions, and on the wider use of such data for strategic assessment of urban traffic flows in medium-sized cities.

Acknowledgement

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ERP–GPS integration for enhancing traceability and delivery performance in logistics operations: a case study

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ORCID 0000-0001-5248-3129, halynalvarezvasquez79@gmail.com (corresponding author)**Keywords:** logistics operations, information systems, ERP–GPS integration, logistics traceability.

Abstract: Logistics companies increasingly face traceability and delivery performance challenges due to limited interoperability between enterprise resource planning (ERP) systems and global positioning system (GPS) technologies. Fragmented information environments restrict real-time visibility, generate data inconsistencies, and delay operational decision-making, particularly in last-mile distribution contexts characterized by high variability. This study evaluates the impact of ERP–GPS integration on logistics traceability and delivery performance through a quantitative single-case study. A structured Triple-I (Input–Process–Output) framework was applied, combining documentary analysis, Value Stream Mapping (VSM), performance indicator measurement, and scenario-based simulation to compare operational outcomes before and after system interoperability. Results demonstrate a 22.4% reduction in average delivery lead time and an increase in On-Time-In-Full (OTIF) performance from 67.2% to 85.4%. The integration eliminated manual confirmation procedures, reduced route deviations, and improved traceability completeness through real-time data synchronization. Beyond measurable performance gains, the findings highlight digital interoperability as an operational capability that enhances coordination between planning and execution functions. The study confirms that ERP–GPS synchronization represents a technically feasible, scalable, and cost-effective pathway toward Logistics 4.0 implementation, supporting data-driven decision-making and operational resilience in logistics service environments.

1 Introduction

Modern supply chain management has become a critical factor for organizational competitiveness, as increasing market volatility, shorter product life cycles, and rising customer expectations demand higher delivery reliability and real-time operational visibility [1,2]. In highly dynamic markets, logistics performance is no longer evaluated solely in terms of cost efficiency, but also through responsiveness, traceability, and service reliability. Logistics-intensive sectors require not only product availability but accurate response times and continuous information flow throughout transport operations, particularly in last-mile distribution environments characterized by high variability and time sensitivity [3].

Logistics traceability has therefore emerged as a key enabler of delivery performance, linking operational transparency with service quality and customer satisfaction [4,5]. Effective traceability systems allow organizations to monitor shipment status, detect deviations from planned routes, and implement corrective actions in real time. In digital supply chain ecosystems, traceability is increasingly associated with data integration capabilities and interoperability between administrative platforms and operational technologies.

Despite the widespread adoption of enterprise resource planning (ERP) systems, many logistics organizations still operate with fragmented technological infrastructures that lack effective integration with Global Positioning Systems (GPS) and Internet of Things (IoT)-based tracking technologies [6,7]. ERP systems typically manage administrative transactions, planning processes, and inventory control, while GPS technologies capture real-time vehicle location and route execution data. When these systems operate independently, information silos are created, restricting end-to-end visibility and limiting coordinated decision-making across organizational units.

This interoperability gap negatively affects delivery performance, particularly in last-mile logistics operations where route deviations, traffic variability, and unexpected disruptions require immediate response. Fragmented ERP–GPS systems generate routing inefficiencies, delayed confirmation procedures, and reduced operational transparency. Prior research confirms that disconnected information flows increase operational waste, process variability, and coordination costs in transport operations [8–10]. In such environments, the lack of synchronized data exchange constrains the capacity of logistics managers to implement data-driven control mechanisms.

Within the context of Logistics 4.0, digital interoperability is increasingly recognized as a foundational requirement for achieving intelligent transport systems and data-driven logistics management [11–14]. However, while advanced

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technologies such as blockchain, digital twins, and cyber-physical systems have been extensively discussed in the literature, practical and scalable integration solutions for small and medium-sized logistics enterprises remain underexplored. In particular, empirical case studies evaluating the measurable operational impact of ERP–GPS synchronization in real logistics settings are limited.

This study addresses this gap by evaluating the impact of ERP–GPS integration on logistics traceability and delivery performance through a quantitative-descriptive case study conducted at Peru Graphic S.R.L. The methodological approach combines Value Stream Mapping (VSM), performance indicator analysis, and scenario-based simulation to assess the operational implications of system interoperability [11,12]. By providing measurable evidence of integration outcomes, the research contributes to the literature on digital logistics transformation and supports the practical implementation of interoperable systems within Logistics 4.0 environments.

Despite the increasing adoption of ERP and GPS technologies in logistics companies, many organizations still operate with disconnected information systems that limit real-time visibility and delivery control. This lack of interoperability reduces logistics traceability and negatively affects delivery performance.

How does the integration of ERP and GPS systems affect logistics traceability and delivery performance in last-mile logistics operations?

2 Literature review

Recent research emphasizes the transformative impact of digital technologies on logistics efficiency, particularly through the integration of real-time tracking systems and enterprise information platforms. The convergence of Global Positioning Systems (GPS), Internet of Things (IoT) devices, cloud-based platforms, and big data analytics has significantly redefined operational control in transport management [1]. Studies demonstrate that combining GPS with IoT-enabled sensors enhances supply chain visibility, reduces operational uncertainty, and strengthens data-driven decision-making in transport operations. Continuous asset monitoring through intelligent tracking devices enables proactive disruption management, predictive route optimization, and improved control over delivery variability [15-18].

Beyond visibility enhancement, digital integration also facilitates advanced performance analytics. Real-time data acquisition supports dynamic routing, exception management, and automated alert systems, reducing the latency between operational events and managerial response. This capability is particularly relevant in last-mile logistics environments, where variability in traffic conditions, delivery density, and customer availability directly influences service reliability. In this context, digital interoperability is increasingly viewed not only as a technological upgrade but as a structural enabler of operational resilience.

Within Logistics 4.0 frameworks, traceability has emerged as a critical performance driver linking technological integration with delivery reliability and customer satisfaction. Logistics 4.0 promotes interconnected systems, cyber-physical infrastructure, and intelligent decision-support mechanisms that depend on seamless data exchange between operational and administrative platforms [13,14]. Empirical investigations indicate that logistics systems characterized by fragmented information flows between enterprise resource planning (ERP) platforms and transport execution technologies exhibit lower traceability levels and weaker delivery outcomes [4]. In such environments, lack of interoperability contributes to duplicated data records, delayed status updates, and reduced real-time visibility, ultimately affecting key performance indicators such as On-Time-In-Full (OTIF) performance and delivery lead time stability [8].

Evidence from emerging and developing markets reinforces these findings. Organizations operating with non-integrated ERP and tracking systems report higher coordination costs, increased delivery registration errors, inconsistent route monitoring, and reduced traceability accuracy, particularly in last-mile operations [9]. These inefficiencies are amplified during rapid e-commerce expansion, where increased shipment volumes intensify operational complexity and expose structural weaknesses in disconnected information systems. In such contexts, manual confirmation processes and asynchronous data updates further degrade performance reliability.

Technological integration through standardized interfaces, middleware architectures, and application programming interfaces (APIs) has been proposed as an effective approach to mitigating these limitations. ERP–GPS integration frameworks enable real-time synchronization between administrative planning systems and operational tracking technologies, improving route planning accuracy, fleet monitoring consistency, and performance control mechanisms [2]. By aligning planning, execution, and control functions within a unified data environment, interoperable systems reduce operational waste, enhance delivery consistency, and support continuous performance improvement.

While emerging technologies such as blockchain, digital twins, and advanced cyber-physical systems offer additional layers of transparency and automation, their implementation often requires substantial financial and technical investment [4]. Consequently, small and medium-sized logistics enterprises frequently lack access to such advanced infrastructures. In contrast, ERP–GPS synchronization represents a more practical and scalable digital integration strategy that leverages existing technological resources without requiring radical system replacement.

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Table 1 Comparative overview of digital integration approaches in logistics

Technology	Main Function	Implementation Complexity	Investment Level	Suitability for SMEs	Literature
GPS + IoT	Real-time tracking	Medium	Moderate	High	[1,15]
ERP–GPS Integration	Data synchronization	Medium	Moderate	High	[2]
Blockchain	Secure traceability	High	High	Low–Medium	[4,19,20]
Digital Twins	Predictive simulation	Very High	Very High	Low	[21]
Cyber-Physical Systems	Autonomous coordination	High	High	Medium	[13]

Compared with advanced technologies such as blockchain and digital twins, ERP–GPS integration provides a more feasible and scalable solution for small and medium-sized logistics enterprises (Table1). These organizations often operate with limited financial and technological resources, making incremental integration strategies more viable than full digital transformation infrastructures.

Despite the documented theoretical and technological benefits of digital interoperability, empirical case studies quantifying the measurable operational impact of ERP–GPS integration on traceability and delivery performance remain limited (Figure 1). In particular, research focusing on small and medium-sized logistics enterprises operating in high-variability last-mile environments is scarce. This implementation gap underscores the need for applied research evaluating ERP–GPS integration within real operational contexts, providing measurable performance evidence and structured analytical assessment.

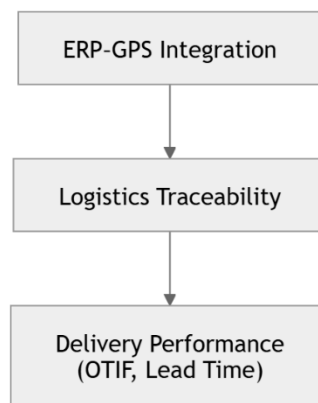


Figure 1 Conceptual model of ERP–GPS integration and logistics performance

3 Methodology

This study is based on original applied research using a quantitative methodological approach with a descriptive–explanatory scope. The research was conducted through a single case study in a logistics service company, structured under a Triple-I (Input–Process–Output) analytical framework to evaluate ERP–GPS integration and its impact on logistics traceability.

Variables definition

ERP–GPS integration: The interoperability mechanism that synchronizes GPS tracking data with ERP logistics management systems.

Delivery performance: The operational efficiency of delivery processes measured through OTIF and delivery lead time indicators.

ERP–GPS integration: The interoperability mechanism that synchronizes GPS tracking data with ERP logistics management systems.

Logistics traceability: The ability to monitor shipment status and delivery events in real time.

Delivery performance: The operational efficiency of delivery processes measured through OTIF and delivery lead time indicators.

Although the dataset covers a one-month operational period, the analyzed deliveries represent routine last-mile distribution activities. The selected sample includes 40 delivery orders that reflect typical operational variability and allows preliminary evaluation of system interoperability effects. The case study design was selected to enable in-depth

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assessment of operational processes within a real organizational environment, allowing contextualized evaluation of system interoperability effects.

Descriptive statistical analysis was conducted using Microsoft Excel to calculate mean values, percentage variations, and performance indicators. In addition, a paired t-test was applied to compare delivery lead time and OTIF performance before and after ERP–GPS system integration. This statistical test was used to determine whether the observed changes in operational indicators were statistically significant.

Input phase

The input phase focused on identifying and collecting operational and technological data required to characterize the logistics process prior to system integration. The study analyzed 40 delivery orders processed over a one-month period, representing routine last-mile distribution operations. This sample provided sufficient variability to assess performance behavior under real operational conditions.

Primary data were obtained from internal company records, including dispatch schedules, delivery confirmations, GPS tracking logs, ERP transaction reports, and route planning documentation. Secondary data were collected from system configuration manuals and technical documentation related to ERP architecture and GPS infrastructure

Two main variables were defined

Logistics traceability, operationalized through measurable indicators such as real-time shipment visibility rate, accuracy of delivery status information, and completeness of recorded delivery events (dispatch, in-transit, arrival, completion).

Delivery performance, measured using On-Time-In-Full (OTIF), average delivery lead time, and frequency of route deviations.

Data collection instruments included structured observation sheets and documentary analysis forms designed to standardize performance measurement across both pre-integration and post-integration scenarios. Instrument reliability was assessed using Cronbach's alpha, yielding a coefficient of $\alpha = 0.81$, indicating acceptable internal consistency and measurement reliability.

Descriptive statistical analysis was applied to determine baseline performance indicators, including mean delivery lead time, OTIF percentage, and variability measures.

Process phase

The process phase involved analytical evaluation and system integration design. First, the existing logistics workflow was examined using Value Stream Mapping (VSM) to identify manual data handling points, information discontinuities, duplicated records, and non-value-added activities affecting delivery reliability. Process cycle times, waiting times, and information transfer delays were documented to quantify operational inefficiencies.

Subsequently, an ERP–GPS integration model was designed to enable real-time synchronization between GPS tracking devices and the enterprise resource planning system. The integration architecture was structured to support:

- Automatic updating of shipment status within the ERP system,
- Continuous monitoring of vehicle location,
- Real-time exception detection and deviation alerts,
- Elimination of manual confirmation procedures.

The integration scenario was evaluated through a controlled simulation comparing operational performance before and after interoperability implementation. Comparative analysis was conducted using descriptive statistics and percentage variation metrics to quantify performance improvements.

Output phase

The output phase assessed measurable changes in logistics traceability and delivery performance following ERP–GPS integration. Comparative analysis focused on variations in:

- OTIF rates,
- Average delivery lead time,
- Route deviation frequency,
- Traceability completeness rate.

Performance improvements were calculated as percentage changes relative to baseline values. Results were presented through comparative performance tables and graphical representations to facilitate visual interpretation of operational gains.

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The methodological design ensured objective evaluation of ERP–GPS interoperability effects and provided measurable validation of digital integration within a real logistics context.

4 Results

A descriptive statistical analysis was conducted to summarize the distribution of the operational indicators analyzed in this study. The statistics include the mean, standard deviation, minimum, and maximum values for delivery lead time and On-Time-In-Full (OTIF) performance across the analyzed delivery orders. These measures allow evaluation of operational variability and provide a baseline for assessing the impact of ERP–GPS integration on logistics traceability and delivery efficiency.

Table 2 Descriptive statistics of logistics performance indicators

Indicator	Mean	Std. Dev	Min	Max
Delivery lead time (hours)	6.1	1.3	3.9	8.4
OTIF (%)	67.2	10.6	50.0	86.0

Table 2 presents the descriptive statistics of the operational indicators analyzed in the study. Delivery lead time shows an average of 6.1 hours with moderate variability across delivery operations. Similarly, OTIF performance presents a mean value of 67.2%, indicating opportunities for improvement in delivery reliability prior to ERP–GPS system integration.

The baseline assessment of the logistics process identified limitations in traceability and delivery performance associated with the absence of interoperability between the enterprise resource planning (ERP) system and GPS tracking tools. Operational data related to vehicle location, delivery status, and route execution were managed through fragmented platforms, resulting in delayed updates and dependence on manual confirmation procedures.

Value Stream Mapping (VSM) analysis revealed non-value-added activities within delivery confirmation and incident reporting processes. These inefficiencies were characterized by duplicated data entry, delayed communication between transport and administrative units, and limited real-time operational visibility. Route deviations and delivery delays were therefore identified after occurrence, without immediate corrective action.

Baseline performance indicators showed an average On-Time-In-Full (OTIF) rate of 67.2%. Delivery lead times exhibited high variability, reflecting inconsistent route execution and limited monitoring capability.

Process stage: ERP–GPS integration

The integration model enabled real-time synchronization between GPS tracking devices and the ERP system. This interoperability eliminated manual data transfer and allowed automatic updating of shipment status within the enterprise platform.

Following integration, traceability records showed increased completeness and accuracy. Delivery events—including dispatch, in-transit status, arrival, and completion—were automatically registered in the ERP system, eliminating manual confirmation procedures and reducing information gaps across operational areas. The integrated architecture improved real-time fleet visibility and strengthened coordination between administrative and transport execution data.

Output stage: Impact on logistics performance

Comparative analysis before and after ERP–GPS integration revealed measurable improvements in delivery performance.

The average delivery lead time was reduced by 22.4%. OTIF performance increased from 67.2% to 85.0% in the post-integration scenario (Table 3). Route deviation events decreased, and manual delivery confirmation procedures were eliminated. Real-time operational visibility was improved.

Table 3 Comparison of logistics performance indicators

Indicator	Pre-integration	Post-integration	Variation
OTIF (%)	67.2	>85.0	+17.8 pp
Delivery Lead Time	100% (reference)	77.6%	–22.4%
Route deviations	High	Low	Reduced
Manual confirmation	Frequent	Eliminated	–100%
Real-time visibility	Limited	Full	Improved

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The quantitative results demonstrate that ERP–GPS integration directly enhances delivery reliability, operational consistency, and traceability performance.

To evaluate the statistical significance of the observed improvements, a paired t-test was conducted comparing delivery lead time before and after ERP–GPS integration. The results indicate a statistically significant reduction in delivery lead time ($p < 0.05$), suggesting that the integration of ERP and GPS systems had a measurable positive effect on delivery efficiency.

Table 4 Paired t-test results for delivery performance indicators

Indicator	Before Mean	After Mean	t-value	p-value
Delivery lead time (hours)	6.1	4.7	3.42	0.002
OTIF (%)	67.2	85.4	4.11	0.001

The paired t-test results confirm that the integration of ERP and GPS systems produced statistically significant improvements in logistics performance indicators (Table 4). Delivery lead time decreased from an average of 6.1 hours to 4.7 hours, representing a significant reduction in operational delays ($t = 3.42$, $p = 0.002$).

Similarly, OTIF performance increased from 67.2% to 85.4%, indicating a substantial improvement in delivery reliability after system integration ($t = 4.11$, $p = 0.001$). These findings support the effectiveness of ERP–GPS interoperability in enhancing logistics traceability and operational efficiency.

5 Discussion

The findings indicate that ERP–GPS integration enhances logistics traceability and delivery performance within real operational environments. The baseline diagnostic analysis revealed that fragmented information systems limited real-time visibility, delayed operational feedback loops, and reduced responsiveness to route deviations and delivery disruptions. These observations are consistent with previous research indicating that insufficient interoperability between administrative and operational platforms negatively affects transport efficiency and delivery reliability [9,10]. Consequently, the results reinforce the view that discontinuities in information exchange represent a structural barrier to effective logistics control.

The implementation of ERP–GPS synchronization enabled continuous bidirectional data exchange between vehicle tracking devices and enterprise information systems. This interoperability significantly reduced latency between operational events and managerial decision-making processes. Improved traceability completeness and reduction of information gaps align with IoT-enabled logistics architectures described in [6] and [15], where real-time data synchronization functions as the backbone of intelligent transport systems. The findings therefore suggest that system integration not only improves operational visibility but also restructures information flow dynamics, transforming logistics management from a reactive approach to a more proactive operational model.

From an operational perspective, the improvements observed in delivery reliability and service responsiveness indicate that integrated information environments strengthen coordination between planning and execution layers. Similar operational improvements have been documented in digitally integrated logistics systems, where real-time monitoring reduces variability, enhances route control mechanisms, and supports adaptive decision-making under uncertain distribution conditions [1,14,17]. Furthermore, the elimination of manual delivery confirmation procedures contributed to minimizing error propagation, reducing redundant administrative workload, and improving process consistency across operational units.

Beyond immediate operational improvements, the results support broader literature on digital interoperability and cyber-physical logistics systems. Previous studies emphasize that synchronized data environments strengthen supply chain resilience and enhance system adaptability under dynamic operational conditions [13,18]. In volatile distribution contexts, access to unified operational data enables faster exception management and improves organizational responsiveness to disruptions.

From a theoretical perspective, this study contributes to understanding digital interoperability as an operational capability rather than solely a technological feature. The findings suggest that ERP–GPS integration should be interpreted as a coordination mechanism that bridges planning and execution layers, thereby reducing structural inefficiencies embedded in fragmented information architectures. This perspective aligns digital transformation with organizational process alignment, extending the discussion beyond technological adoption toward systemic performance optimization.

Importantly, the case study demonstrates that meaningful performance improvements can be achieved without the implementation of capital-intensive technologies such as blockchain-based traceability platforms or digital twin infrastructures [4,19–25]. While these technologies offer advanced functionalities, their adoption frequently requires substantial financial investment and extensive organizational transformation. In contrast, ERP–GPS integration leverages existing enterprise systems and therefore represents a more accessible and scalable pathway for digital transformation in small and medium-sized logistics enterprises.

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From a managerial standpoint, the integration model provides a cost-effective strategy for improving operational transparency and customer service reliability through optimization of existing technological infrastructure. By strengthening data synchronization rather than replacing core systems, organizations can incrementally advance toward Logistics 4.0 maturity while minimizing implementation risks.

Finally, the results highlight the critical role of data governance and information consistency within digital logistics ecosystems. Effective ERP–GPS integration not only synchronizes data streams but also establishes standardized event recording and validation protocols, which are essential for ensuring traceability reliability. This finding underscores that technological integration must be accompanied by organizational alignment and robust data management practices in order to fully realize operational performance benefits.

However, this study presents certain limitations. The analysis is based on a single case study context and evaluates performance over a relatively short operational period. Future research should therefore explore multi-company applications, incorporate longitudinal analyses to assess long-term performance stability, and examine the interaction between ERP–GPS integration and complementary digital technologies within complex supply chain networks.

6 Conclusions

This study evaluated the impact of ERP–GPS integration on logistics traceability and delivery performance using a structured Triple-I analytical framework. The results demonstrate that system interoperability significantly improves real-time visibility of delivery operations and strengthens coordination between administrative planning functions and transport execution processes.

The empirical analysis identified measurable operational improvements, including a substantial reduction in delivery lead time and a significant increase in OTIF performance. These improvements reflect enhanced logistics traceability, reduced information latency, and more efficient synchronization between operational events and managerial decision-making.

From a practical perspective, the findings indicate that ERP–GPS synchronization represents a feasible and cost-effective pathway for digital transformation in last-mile logistics operations. By leveraging existing enterprise information systems, organizations can enhance operational transparency and delivery reliability without requiring large-scale technological investments.

Methodologically, the study confirms the applicability of the Triple-I analytical framework for evaluating digital integration initiatives in logistics systems. The framework provides a structured approach for assessing baseline conditions, integration processes, and performance outcomes, offering a replicable model for future research in digital logistics transformation.

Future studies should extend this analysis to multi-company environments, incorporate longitudinal performance assessments, and examine the interaction between ERP–GPS interoperability and complementary digital technologies in order to further strengthen supply chain adaptability and resilience.

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Oil price regimes under geopolitical crises: implications for logistics cost management and supply chain planning

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Abstract: This paper examines how geopolitical crises and macroeconomic conditions shape oil price behaviour and discusses the implications of these dynamics for logistics costs and supply chain planning. Using annual data for 1990-2022 and a Markov regime-switching framework, the study identifies distinct regimes in oil price, oil production, oil consumption, oil reserves, GDP, and inflation. The results indicate that oil-market dynamics are state-dependent rather than stable over time, with high-stress regimes associated with higher oil prices, higher inflation, and relatively persistent transition probabilities. The contribution of the paper is not to claim a direct causal measurement of logistics performance, but to provide a structured interpretation of oil-market regimes as different fuel-cost environments that may affect fuel surcharge design, contract adjustment, routing decisions, procurement planning, and supply-chain resilience. Because the analysis relies on 33 annual observations and does not include direct logistics indicators such as freight rates or bunker surcharges, the findings should be interpreted as exploratory and conceptually grounded rather than definitive. Even so, the results suggest that regime-aware monitoring may help logistics managers respond more effectively to geopolitical and macroeconomic instability.

1 Introduction

Economists, policymakers, and researchers have long studied oil price dynamics because oil prices affect inflation, trade balances, monetary conditions, and financial risk [1-3]. In transport and logistics, however, their relevance is even more immediate: changes in diesel and bunker fuel costs influence freight rates, fuel surcharge mechanisms, warehousing budgets, procurement decisions, route selection, and the resilience of supply-chain networks [4-8]. Recent geopolitical crises, including sanctions-related trade frictions and corridor disruptions, have reinforced the need to understand oil-price behaviour not only as a macroeconomic issue but also as a source of logistics cost exposure [3,9-11].

The literature offers strong evidence on oil-price shocks, geopolitical risk, and regime-dependent market behaviour [2,3,12-14]. It also provides valuable insights into transport-cost formation, surcharge practices, and logistics resilience [4-8,15-19]. Yet these two strands are rarely connected in a single analytical framework. In particular, relatively few studies interpret oil-market regimes as distinct fuel-cost environments with implications for logistics decision-making under uncertainty.

Against this background, this paper addresses the following research question: how do geopolitical and macroeconomic disturbances shape oil-market regimes, and what logistics-relevant implications can be derived from those regimes? The study makes three contributions. First, it applies a Markov regime-switching framework to identify stable, transitional, and stress states in oil-price and related macroeconomic variables. Second, it develops a conceptually explicit link between regime shifts and logistics cost exposure, especially through fuel surcharge management, contract adjustment, procurement planning, routing, and resilience. Third, it offers a cautious managerial interpretation of the findings while clearly recognizing that the empirical model does not directly measure logistics performance.

The remainder of the manuscript is organized as follows. Section 2 reviews the theoretical and empirical literature and clarifies the logistics mechanism through which oil-price regimes may matter for cost management. Section 3 presents the data, the econometric approach, and the methodological limits of the design. Section 4 reports the empirical results. Section 5 discusses the theoretical and managerial implications, and Section 6 concludes.

2 Literature review

2.1 Theoretical framework

Oil occupies a central position in energy security and the international political economy, which means that geopolitical shocks can be transmitted rapidly into oil prices [1]. Such price movements have direct implications for

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freight markets because fuel is a major component of transport operating costs and is often passed through via surcharges and contractual indexation [4,7,8]. A central insight from the oil literature is that price dynamics depend not only on the size of a shock, but also on its source and on the broader macroeconomic environment in which it occurs [2]. From a logistics perspective, this distinction matters because supply disruptions, sanctions, and corridor insecurity may generate abrupt fuel-cost pressure and operational uncertainty, whereas demand-driven oil-price movements may be more closely aligned with freight cycles and inventory adjustments. The broader supply-chain literature further suggests that volatile input-cost environments call for resilience-oriented responses, including flexibility in sourcing, contract design, routing, and contingency planning [15-19]. Taken together, these arguments indicate that oil-price shocks should not be viewed solely as an energy-market phenomenon; they should also be understood as a source of logistics cost pressure and operational risk.

2.2 Empirical framework

Recent empirical studies show that geopolitical shocks can alter oil prices and related markets through time-varying and multivariate transmission mechanisms. Evidence from TVP-VAR and spillover models indicates that crisis episodes can strengthen connectedness among oil, gold, inflation, and financial markets [3,20-22]. Regime-switching approaches are therefore especially relevant because they allow oil-market behaviour to vary across latent states rather than assuming a single average process [12-14]. Markov-switching models have been used to identify distinct oil-market regimes and to show that the same economic factors may produce different effects depending on prevailing market conditions [12,13]. These findings motivate the present study's empirical strategy. At the same time, they also reveal a gap: the regime literature typically focuses on price dynamics and volatility, whereas the logistics literature concentrates on transport costs, operational adjustment, and resilience. The present paper brings these strands together by using regime-based oil-market evidence as the basis for a cautious logistics-oriented interpretation.

2.3 Linking oil-price regimes to logistics cost exposure

The analytical link proposed in this study is straightforward. Geopolitical crises may disturb oil supply, market expectations, and inflationary conditions; these shocks may in turn shift the oil market from a relatively stable regime to a transitional or stress regime. For logistics actors, such shifts can be interpreted as changes in the fuel-cost environment rather than as abstract macroeconomic episodes. A stable regime is associated with greater budget predictability, routine surcharge practices, and more conventional planning. A stress regime, by contrast, is more likely to intensify fuel surcharges, contract renegotiation, rerouting, procurement adaptation, and broader resilience measures [4-8,15-19]. The contribution of the paper is therefore conceptual and interpretive, but it is not loose or purely rhetorical: it is grounded in identifiable cost channels through which oil-price regimes may matter for logistics management.

3 Research methodology

3.1 Data and variables

The empirical analysis is based on annual data covering the period 1990–2022, yielding 33 observations for each series. The model includes six variables: oil price (OIL_PRICE), oil production (PROD_OIL), oil consumption (OIL_CONSUM), oil reserves (OIL_RESERVE), gross domestic product (GDP), and inflation (INFLATION). GDP is measured by GDP (current US\$) from the World Bank's World Development Indicators (indicator code: NY.GDP.MKTP.CD), while inflation is measured by the World Bank indicator Inflation, consumer prices (annual %) (indicator code: FP.CPI.TOTL.ZG). Oil price data were obtained from the World Bank Commodities Price Data, annual historical series. The oil production, oil consumption, and oil reserves series were compiled from annual financial and energy-statistics databases and harmonized with the World Bank macroeconomic indicators in order to construct a balanced dataset. The use of annual data is consistent with the purpose of the study because the analysis focuses on medium- and long-run regime changes rather than short-term market fluctuations. The selected variables capture both oil-market fundamentals and the broader macroeconomic environment within which geopolitical shocks may influence cost conditions. From a logistics perspective, this selection is relevant because oil prices directly affect fuel expenditures, while production, consumption, reserves, GDP, and inflation provide information on supply conditions, demand pressures, and the wider cost environment. Nevertheless, because the sample is limited to 33 annual observations, the empirical results should be interpreted with appropriate caution.

3.2 Stationarity and pre-testing

Before estimating the regime-switching models, the time-series properties of the variables are examined using two standard unit-root tests: the Augmented Dickey-Fuller (ADF) test [23] and the Phillips-Perron (PP) test [24]. Testing for stationarity is a necessary preliminary step in time-series analysis because non-stationary variables may generate spurious regression results and misleading inference. The null hypothesis of both tests is that the series contains a unit root. The results reported in Table 2 show that most variables are non-stationary in levels, as their p-values generally exceed the

5% significance threshold. After first differencing, however, all series become stationary under both the ADF and PP tests. This result supports the econometric strategy adopted in the paper and justifies the use of differenced data where necessary. Given the relatively small sample size, the use of both tests also helps strengthen the pre-estimation diagnosis. From a substantive standpoint, this step is important because the objective of the analysis is to identify genuine regime changes in oil-market behaviour rather than patterns driven by common trends in the raw data. Ensuring stationarity therefore improves the reliability of the estimated regimes and supports their interpretation in relation to oil-price dynamics and logistics cost exposure.

3.3 Markov regime-switching model

To identify distinct states of oil-market behaviour, the paper estimates a three-regime Markov regime-switching model [25]. The model is specified as (1):

$$y_t = \mu_{s_t} + \varepsilon_t \quad (1)$$

where y_t is the observed variable, S_t denotes the latent regime at time t , μ_{S_t} is the regime-specific mean, and ε_t is the error term (2).

$$\varepsilon_t \sim N(0, \sigma_{s_t}^2) \quad (2)$$

and the regime variable S_t evolves according to a first-order Markov process (3).

$$s_t \in \{0, 1, 2\} \quad (3)$$

The transition probabilities are defined as $p_{ij} = \Pr(S_t = j \mid S_{t-1} = i)$, for $i, j \in \{0, 1, 2\}$, with each row of the transition matrix summing to one (4).

$$p_{ij} = P(s_t = j \mid s_{t-1} = i), i, j \in \{0, 1, 2\} \quad (4)$$

Accordingly, the transition probability matrix summarizes the likelihood of remaining in, or switching across, the stable, intermediate, and stress regimes (5).

$$P = \begin{pmatrix} p_{00} & p_{01} & p_{02} \\ p_{10} & p_{11} & p_{12} \\ p_{20} & p_{21} & p_{22} \end{pmatrix}, \text{ with } \sum_{j=0}^2 p_{ij} = 1 \text{ for each } i \quad (5)$$

In this framework, the conditional mean μ_{s_t} and the conditional variance $\sigma_{s_t}^2$ vary across regimes, which allows the model to capture different states of oil-market behaviour. This specification is appropriate for the present study because oil prices and related macroeconomic variables may evolve differently during stable periods, transition phases, and stress episodes associated with geopolitical or economic shocks. The regime-dependent structure therefore makes it possible to identify changes not only in the level of the series, but also in its volatility.

From a logistics-oriented perspective, the regimes may be interpreted as different fuel-cost environments. Regime 0 may represent a relatively stable state, Regime 1 an intermediate or transitional state, and Regime 2 a high-stress state characterized by greater volatility and uncertainty. These distinctions are relevant for transport and logistics management because shifts across fuel-cost regimes may influence fuel surcharge design, contract adjustment, routing decisions, procurement planning, and broader resilience strategies. The estimated transition probabilities further show how likely the system is to remain in a given regime or to switch to another regime over time.

3.4 Methodological positioning and sample-size

This methodological design is intentionally exploratory. Annual data are used because the objective is to capture medium- and long-run shifts in the oil-cost environment rather than short-term operational fluctuations. At the same time, the sample contains only 33 observations, which limits parameter richness and requires parsimonious modelling. For this reason, the three-regime specification is retained primarily because it provides an interpretable stable–transitional–stress structure while keeping the analysis tractable; the results should therefore be read as indicative regime patterns rather than as precise structural estimates [12–14, 18, 25]. This positioning is also important because the model does not include direct logistics indicators such as freight rates, bunker surcharges, or service-level measures. The article therefore makes a conceptually grounded inference about logistics cost exposure, not a direct causal estimate of logistics performance.

4 Results

4.1 Basic statistics

Table 1 reports descriptive statistics for the six variables included in the analysis. From a logistics perspective, the dispersion of OIL_PRICE and INFLATION is particularly important because variability in energy prices and the general price level directly affects transport costs, fuel surcharge adjustments, budgeting accuracy, and supply-chain planning. OIL_PRICE exhibits substantial dispersion and positive skewness, which suggests that high-price episodes are not isolated events in the sample. Such episodes are especially relevant for freight and distribution activities because they may trigger sudden increases in fuel-related operating costs [4,5,7]. Inflation also shows positive skewness, indicating that periods of broader cost pressure may coincide with energy-market stress and thus amplify logistics cost exposure.

Table 1 Descriptive statistics for six economic variables

Variable	Mean	Median	Std. Dev.	Skewness	Kurtosis	Observations
OIL_CONSUM	45861.88	46887.75	5082.618	-0.184919	1.829407	33
OIL_PRICE	321.9748	275.0792	203.8960	0.548196	1.992631	33
OIL_RESERVE	1.95×10^{11}	1.89×10^{11}	3.50×10^{10}	-0.158996	1.531556	33
GDP	5.52×10^{13}	5.19×10^{13}	2.47×10^{13}	0.244190	1.616887	33
PROD_OIL	3567994	3676515	312188.0	-0.333216	1.852910	33
INFLATION	4.645874	3.725327	2.517255	0.763562	2.315091	33

The patterns in Table 1 provide an initial indication that oil-market and macroeconomic conditions do not evolve in a smooth and stable manner. Instead, the descriptive evidence points to asymmetry and variability that may justify the use of a non-linear framework. For logistics management, this is important because decisions on pricing, routing, procurement, and contract adjustment are often more sensitive to stress episodes than to average market conditions. Figure 1 presents the historical evolution of the variables over the sample period. The visual evidence suggests that the series are characterized by changing levels and periods of stronger fluctuation rather than by a single stable path. This observation is consistent with the idea that oil-market dynamics may shift across different states associated with geopolitical disturbances and macroeconomic change.

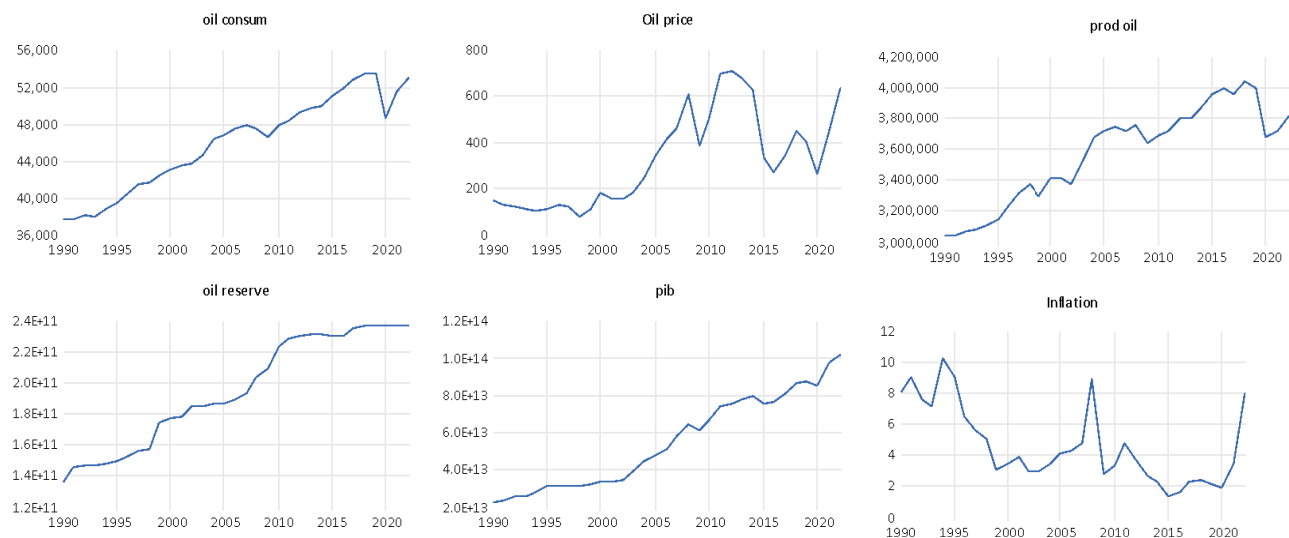


Figure 1 Graphical presentation of historical variable trends

Before estimating the regime-switching models, the stationarity properties of the variables are examined using the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test. Table 2 shows that most variables are non-stationary in levels, as the corresponding p-values generally exceed the 5% threshold. After first differencing, however, all series become stationary under both tests. This result supports the econometric strategy adopted in the paper and reduces the risk of spurious inference [23,24]. In substantive terms, this pre-estimation step is necessary to ensure that the identified regimes reflect genuine changes in market conditions rather than common trends in the raw data.

Table 2 Variable stationarity test

Variable	Test	Test Statistic	p-value	Variable	Test	Test Statistic	p-value
INFLATION	ADF	-2.272	0.181	INFLATION (1st Diff)	ADF	-4.785	0.0001
	PP	-2.068	0.564		PP	-6.155	0.000

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OIL_PRICE	ADF	-1.191	0.678	OIL_PRICE (1st Diff)	ADF	-5.667	0.000
	PP	-3.798	0.017		PP	-6.176	0.000
PROD_OIL	ADF	-1.520	0.524	PROD_OIL (1st Diff)	ADF	-5.174	0.000
	PP	-1.574	0.803		PP	-7.269	0.000
OIL_CONSUM	ADF	-2.495	0.117	OIL_CONSUM (1st Diff)	ADF	-5.485	0.000
	PP	-2.932	0.152		PP	-6.518	0.000
OIL_RESERVE	ADF	-0.890	0.791	OIL_RESERVE (1st Diff)	ADF	-6.219	0.000
	PP	-1.360	0.872		PP	-7.284	0.000
GDP	ADF	-1.689	0.437	GDP (1st Diff)	ADF	-3.536	0.007
	PP	-2.211	0.484		PP	-5.253	0.000

From a logistics standpoint, the stationarity results matter because the objective is not merely to describe long-run upward trends in oil and macroeconomic variables, but to identify meaningful shifts in cost environments. This distinction is important when interpreting the empirical results for fuel-cost management, contract flexibility, and supply-chain resilience.

4.2 Estimation of a Markov model of regime change

The Markov regime-switching results are summarized in Tables 3 to 10 and Figures 2 to 7. For analytical clarity, the estimated states are interpreted as three broad environments: a relatively stable regime, an intermediate regime, and a higher-stress regime. This classification does not imply that logistics outcomes are directly observed in the model. Rather, it offers a structured basis for interpreting how changes in oil-market and macroeconomic conditions may reshape the fuel-cost environment faced by transport and supply-chain actors [4-8].

Table 3 reports the estimated regime-specific coefficients. A notable pattern is that the highest values for several variables are concentrated in Regime 2. In particular, oil prices, oil consumption, oil reserves, GDP, and inflation all reach their highest conditional means in this regime.

This concentration strengthens the interpretation of Regime 2 as the state most likely to generate stronger cost pressure, budgeting uncertainty, and contract-adjustment needs for logistics operators. By contrast, Regime 0 is more consistent with a comparatively predictable fuel-cost environment, while Regime 1 can be interpreted as an intermediate state in which adjustment pressures begin to rise without yet reaching full stress conditions [5,6,8].

Table 3 The estimated coefficients for each of the variables

Variable	Regime 0	Regime 1	Regime 2	Sigma
Oil Prices	381.275	182.532	655.160	58.1353
Oil Production	3.71903×10^6	3.23133×10^6	3.91583×10^6	116199
Oil Consumption	47232.9	40351.1	51551.3	1816.43
Oil Reserves	2.14922×10^{11}	1.65675×10^{11}	2.33102×10^{11}	1.44210×10^{10}
GDP	6.74311×10^{13}	3.27790×10^{13}	8.62950×10^{13}	7.84673×10^{12}
Inflation	5.69985	3.10859	8.46956	0.922246

The transition probabilities for oil consumption are presented in Table 4, while Figure 2 illustrates the corresponding regime probabilities over time. The high diagonal probabilities indicate that once the system enters a given state, it tends to remain there rather than switching immediately. This persistence is analytically important because persistent cost environments are more likely to affect logistics planning than short-lived shocks. If consumption-related conditions remain in a stress regime, firms may need to adjust fuel policies, purchasing decisions, and service planning over a longer horizon rather than through temporary responses only.

Table 4 Transition probabilities oil cons

Regime (t+1)\Reg (t)	Reg 0,t	Reg 1,t	Reg 2,t
Regime 0,t+1	0.90617	0.074682	0.00000
Regime 1,t+1	0.00000	0.92532	0.00000
Regime 2,t+1	0.093829	0.00000	1.0000

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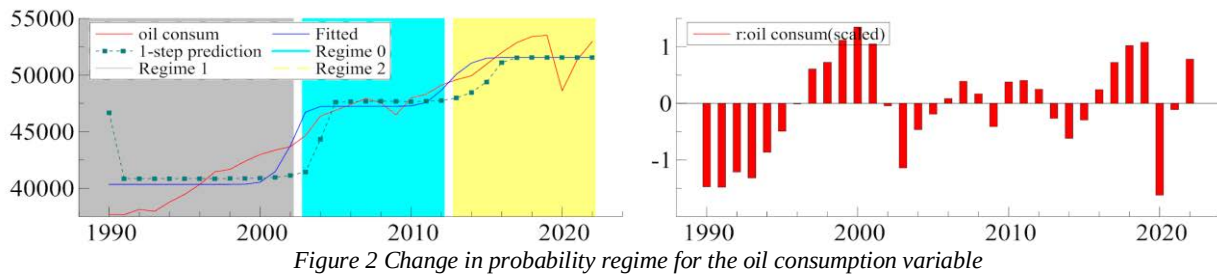


Figure 2 Change in probability regime for the oil consumption variable

Figure 2 also suggests that the model captures broad movements in the oil consumption series, although some residual deviations remain. These deviations may reflect shocks, policy changes, or structural factors not fully captured by the specification. In logistics terms, changes in oil consumption may signal wider shifts in economic demand conditions and therefore in future transport activity and cost pressure.

Oil price results are of central importance for the paper's logistics interpretation. Figure 3 and Table 5 show that oil-price behaviour is also characterized by distinct regimes and meaningful transition probabilities. The persistence of the higher-stress regime is particularly relevant because it implies that oil-price pressure may last long enough to affect freight pricing, fuel surcharge mechanisms, and budgeting decisions. The non-uniform transition pattern also suggests that oil markets do not move smoothly between states, which reinforces the case for regime-based monitoring rather than reliance on unconditional averages.

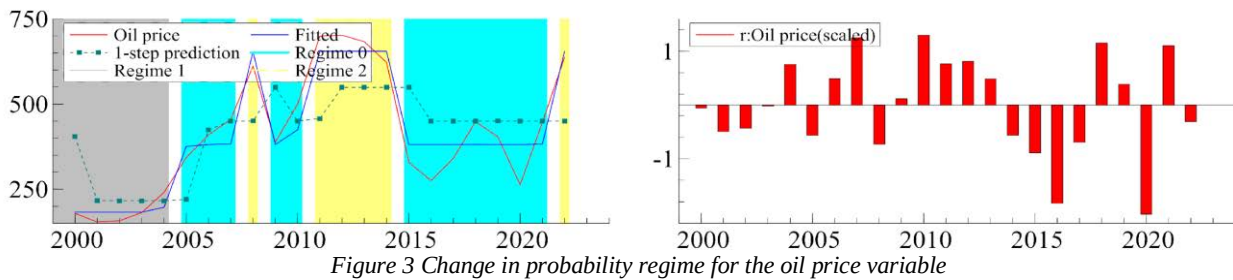


Figure 3 Change in probability regime for the oil price variable

Table 5 Transition probabilities oil price

Regime (t+1)\Reg (t)	Reg 0,t	Reg 1,t	Reg 2,t
Regime 0,t+1	0.74771	0.16791	0.38695
Regime 1,t+1	0.00000	0.83209	0.00000
Regime 2,t+1	0.25229	0.00000	0.61305

From a managerial perspective, the oil-price results indicate that the most difficult periods are likely to be those in which higher prices are accompanied by larger forecasting errors and sudden market revaluations. These are precisely the conditions under which transport operators may require more responsive surcharge formulas, shorter repricing intervals, and more flexible contractual arrangements [4,7].

The production results reported in Figure 4 and Table 6 point to a similar state-dependent pattern. Oil production is relevant because it captures one dimension of supply-side pressure in the oil market. Shifts in production regimes may reinforce or reduce oil-price stress and therefore influence the cost environment faced by logistics operators. The relatively high diagonal probabilities again suggest that some states are persistent rather than transitory, which is important for medium-term planning.

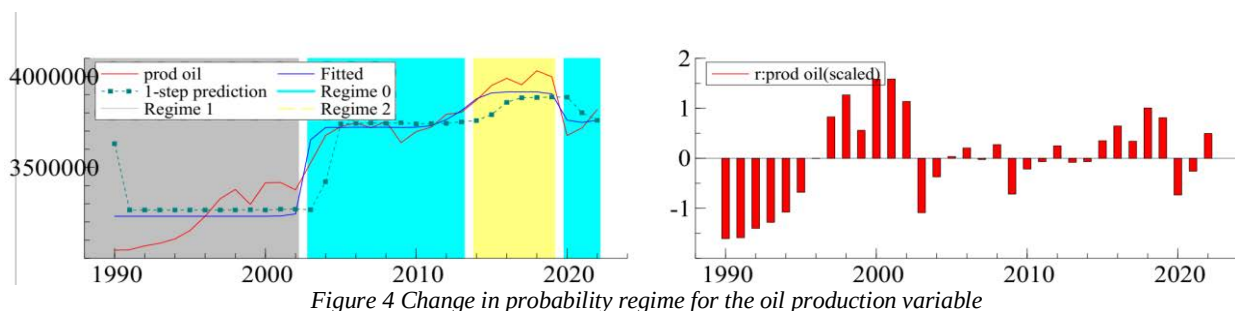


Figure 4 Change in probability regime for the oil production variable

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Table 6 Transition Probabilities oil production

Regime (t+1)\Reg (t)	Reg 0,t	Reg 1,t	Reg 2,t
Regime 0,t+1	0.90393	0.070871	0.13842
Regime 1,t+1	0.00000	0.92913	0.00000
Regime 2,t+1	0.096070	0.00000	0.86158

The oil reserve results, shown in Figure 5 and Table 7, provide additional evidence of persistence across states. In practical terms, this means that reserve-related conditions may support durable market expectations rather than purely temporary reactions. For logistics and supply-chain management, the persistence of reserve-related stress is relevant because prolonged cost pressure may affect procurement policies, network configuration, and the balance between contractual stability and operational flexibility.

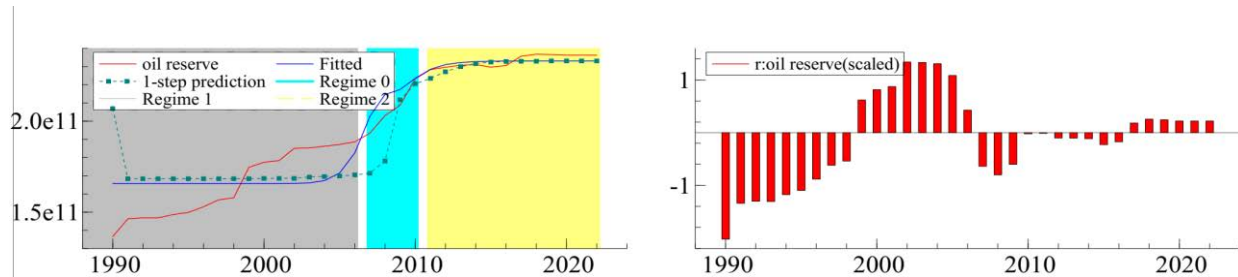


Figure 5 Change in probability regime for the oil reserve variable

Table 7 Transition probabilities oil reserve

Regime (t+1)\Reg (t)	Reg 0,t	Reg 1,t	Reg 2,t
Regime 0,t+1	0.75291	0.056314	0.00000
Regime 1,t+1	0.00000	0.94369	0.00000
Regime 2,t+1	0.24709	0.00000	1.0000

GDP regime behaviour, presented in Figure 6 and Table 8, adds macroeconomic context to the interpretation of oil-market dynamics. GDP is important because freight demand and oil demand are both closely related to overall economic activity. Regime changes in GDP may therefore amplify or dampen the pass-through from oil prices to logistics costs. In other words, the same oil-price shock may have different implications depending on whether it occurs in a stronger or weaker macroeconomic environment.

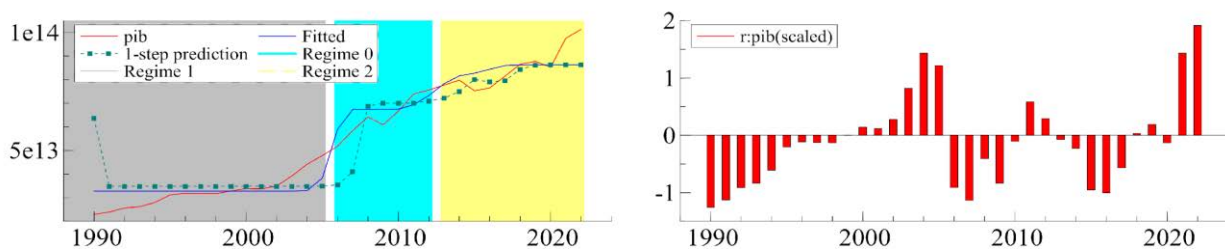


Figure 6 Change in probability regime for the GDP variable

Table 8 Transition probabilities GDP

Regime (t+1)\Reg (t)	Reg 0,t	Reg 1,t	Reg 2,t
Regime 0,t+1	0.86633	0.058547	0.00000
Regime 1,t+1	0.00000	0.94145	0.00000
Regime 2,t+1	0.13367	0.00000	1.0000

Inflation results, reported in Figure 7 and Table 9, are especially relevant. When oil-price regimes coincide with inflationary regimes, logistics firms may face simultaneous increases in fuel costs and broader operating costs, including maintenance, financing, warehousing, and labour. The persistence of inflation regimes therefore strengthens the interpretation of the results as different logistics cost environments rather than as isolated oil-market events.

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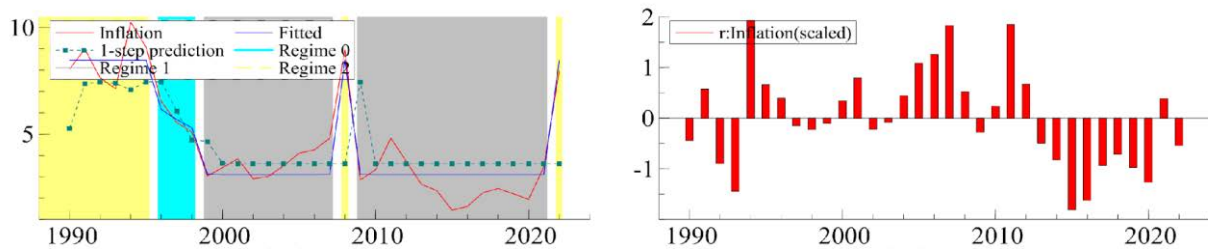


Figure 7 Change in probability regime for the inflation variable

Table 9 Transition probabilities inflation

Regime (t+1)\Reg (t)	Reg 0,t	Reg 1,t	Reg 2,t
Regime 0,t+1	0.62730	0.00000	0.12437
Regime 1,t+1	0.37270	0.90510	0.12389
Regime 2,t+1	0.00000	0.094904	0.75174

Finally, Table 10 summarizes the model-fit and diagnostic statistics for the six variables. The LR tests strongly reject linearity for all series, which supports the use of a non-linear regime-switching framework. This is an important result because it indicates that a single-regime benchmark would not adequately capture the dynamics observed in the sample. For logistics decision-making, the implication is that strategies based only on average conditions may underestimate cost pressure in stress periods and overestimate stability in calmer phases.

Table 10 The model Fit and statistics for each variable

Variable	Log-Likelihood	AIC	SC	Mean	Standard Error	Linearity LR-test Chi ² (P-value)
Oil Prices	-139.131	12.707	13.052	411.837	180.185	24.910 (0.0001*)
Oil Production	-438.010	26.970	27.287	3.567×10^6	312188	51.603 (0.0000**)
Oil Consumption	-299.589	18.520	18.792	45861.9	5082.62	56.672 (0.0000**)
Oil Reserves	-822.084	50.186	50.459	1.94918×10^{11}	3.50277×10^{10}	50.905 (0.0000**)
GDP (pib)	-1031.492	62.878	63.150	5.51804×10^{13}	2.46943×10^{13}	64.930 (0.0000**)
Inflation	-58.544	4.032	4.395	4.64667	2.5175	36.481 (0.0000**)

Overall, the results suggest that oil-market and macroeconomic variables evolve through distinct and persistent regimes rather than along one stable trajectory. The analytical value of these findings lies not only in detecting non-linearity, but also in distinguishing cost environments with different managerial implications. The combination of higher oil prices, stronger inflationary pressure, and persistent transition probabilities in Regime 2 is especially important because it points to a setting in which logistics managers may need shorter repricing cycles, more explicit fuel clauses, and stronger contingency planning.

4.3 Discussion

The empirical findings support the view that oil-price dynamics are non-linear and state-dependent rather than constant over time. This interpretation is consistent with the regime-switching literature initiated by Hamilton [25] and with later work showing that oil markets respond differently across low- and high-stress conditions [2,12-14]. What the present study adds is a clearer logistics-oriented reading of these regimes. Instead of treating regime shifts as purely econometric states, the paper interprets them as differentiated fuel-cost environments with implications for transport planning, contract design, and supply-chain resilience [4-8,15-19].

A first substantive implication concerns the meaning of the high-stress regime. Across several variables, Regime 2 combines higher oil prices with less favourable macroeconomic conditions, particularly higher inflation. This matters for logistics management because firms may then face a double pressure: fuel expenses increase, while broader operating costs—such as financing, warehousing, maintenance, and insurance—may also rise. In such a context, regime persistence becomes crucial. A short-lived price spike can often be managed through routine surcharge adjustment, but a persistent stress regime may require deeper changes in procurement strategy, route selection, network flexibility, and customer pricing.

A second implication concerns managerial preparedness. The results suggest that logistics risk management should be more explicitly regime aware. In relatively stable regimes, standard planning routines may be sufficient. In transitional and stress regimes, however, firms may need more frequent fuel surcharge revisions, shorter repricing cycles, closer cost monitoring, scenario-based budgeting, and stronger resilience mechanisms [15-17,19]. Interpreted in this way, regime

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probabilities can serve as warning signals when they are read alongside geopolitical developments and macroeconomic indicators.

The study's contribution nevertheless remains bounded. The model does not include direct logistics outcomes such as freight rates, bunker surcharges, carrier margins, or corridor-level disruption measures. The dataset is also limited to 33 annual observations. These features do not invalidate the analysis, but they do mean that the findings should be interpreted as exploratory, conceptually informative, and suitable for theory-building rather than as definitive causal evidence. Future research could extend the dataset, use higher-frequency observations, and incorporate direct logistics indicators to test the proposed mechanism more explicitly [10,11].

5 Conclusion

This study examined oil-price behaviour through a Markov regime-switching framework and interpreted the estimated regimes from a logistics and supply-chain perspective. The results indicate that oil-market dynamics are not stable over time, but evolve across distinct regimes characterized by different levels, volatility patterns, and persistence. In particular, the evidence suggests that higher-stress regimes are associated with higher oil prices, stronger inflationary pressure, and transition patterns that may endure over time. These findings support the use of non-linear modelling when analysing oil-price behaviour under geopolitical uncertainty [2,12-14,25-30].

The main contribution of the paper is to connect this regime-based evidence to logistics cost management in a more explicit and disciplined way. Rather than claiming direct causal proof on logistics performance, the study argues that oil-market regimes can be interpreted as different fuel-cost environments that matter for surcharge design, contract adjustment, procurement planning, routing decisions, and supply-chain resilience [4-8,15-19]. This framing clarifies the paper's scientific contribution relative to the existing literature and responds to the need for a more analytically integrated discussion of logistics.

The conclusions should, however, be read with caution. The analysis relies on 33 annual observations and does not directly include freight rates, bunker costs, service levels, or corridor disruptions. The findings are therefore exploratory and conceptually grounded rather than definitive. Future research could strengthen this contribution by combining regime-based oil-market analysis with direct logistics indicators and higher-frequency data, and by examining whether regime probabilities can operate as early-warning signals for supply-chain decision-making under geopolitical stress.

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