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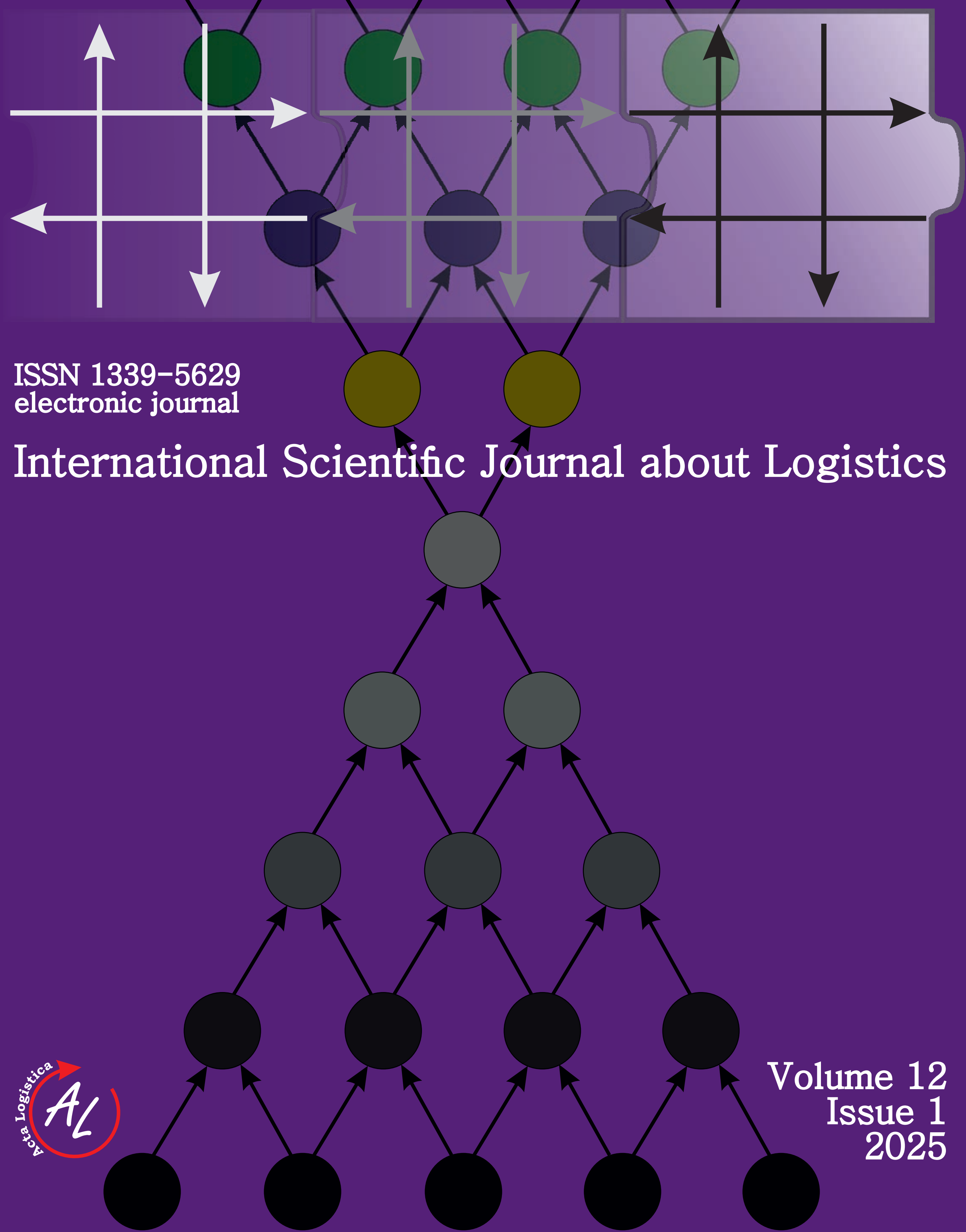

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Evaluating the efficiency of layout solutions through the utilization of simulation software

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Keywords: simulation software, material flow, layout, logistics.
Abstract: The main goal of this article is to identify the relationship between designing a layout and developing an efficient material flow for a new production facility. The article begins with a brief overview of process development and optimization in industrial and logistical environments. It then highlights the significant impact that an effective layout and material flow can have on overall production efficiency. The following sections offer a detailed review of existing literature and theoretical models that support the connection between facility layout design and material flow effectiveness. The article stresses the importance of incorporating modern technologies and methods during the planning phase to boost productivity and minimize waste. In the practical section, the article thoroughly examines the development of the layout solution and provides an in-depth analysis of the material flow, focusing on a specific product. This includes a detailed evaluation of various layout designs and their effects on material handling, storage, and transportation within the facility. The proposed layout and material flow were validated using TX Plant Simulation software, which generated statistical reports and outputs. This software allowed for the modeling and simulation of different scenarios, offering insights into potential bottlenecks and areas for improvement. The simulation results are discussed in detail, highlighting key findings and their implications for the production facility.

1 Introduction

In today's industrial and logistical environments, optimizing and refining processes is increasingly essential for organizations seeking to gain a competitive advantage and achieve long-term success in the 21st century. A critical aspect influencing the effectiveness of these processes is the strategic design of layouts and the flow of materials.

The arrangement of equipment and workstations goes beyond mere spatial organization; it serves as a strategic component that affects various dimensions of business operations. By carefully designing and efficiently managing layouts and material flows, organizations can achieve key objectives such as improving worker productivity, maximizing space and resource use, minimizing waste and inefficiencies, shortening delivery times, and enhancing overall competitiveness [1-3].

Scientific research in layout and material flow is increasingly focused on creating methodologies and technologies that help organizations meet these goals. The integration of advanced technological equipment, automation, and data analysis is crucial for both the design and management of these layouts [4,5].

Furthermore, the incorporation of simulation tools and software, such as TX Plant Simulation, enables the detailed modeling and analysis of potential layout configurations and material flow scenarios before implementation. This predictive approach allows organizations to foresee and mitigate potential issues, ensuring a smoother transition from design to operational phases. By leveraging these technologies, companies can create more resilient and flexible production systems capable of adapting to changing market demands and operational challenges [6].

Additionally, interdisciplinary collaboration among industrial engineers, operations managers, and IT specialists is becoming increasingly important. This collaborative approach ensures that all aspects of layout and material flow design are comprehensively addressed, combining technical expertise with practical insights from daily operations. The result is a more holistic and effective strategy for enhancing overall production efficiency [7].

2 Literature review

In logistics, adaptability refers to the ability of a material flow system to respond to changing conditions through flexibility. Both processes and systems must be capable of evolving and adapting. Achieving these goals depends on the adoption of new technologies that can meet these challenges. In the near future, verifying product functionality within a virtual environment will become a critical standard [8,9]. Growing global competition and increasing customer expectations are driving the need to enhance business processes. Recently, the concept of "lean management" has gained significant attention. This management approach, originating from the Japanese company Toyota, has spread worldwide due to its capacity to respond quickly and flexibly to customer demands. The growing number of case studies highlights its expanding application across various sectors [10-12].

Lean thinking embodies the philosophy and practices of the Toyota Production System (TPS). Within TPS, any resource that does not add value from the customer's perspective is eliminated. The processes are designed to operate using fewer materials, requiring less investment, reducing inventory, minimizing space usage, and involving fewer employees [13-15].

When aiming to improve processes, many companies struggle with the absence of an individual who has a comprehensive understanding of the entire material and information flow, along with all related product processes. A common method to address this gap, while also identifying areas for improvement and proposing company-wide solutions, is value stream mapping. The distinction between process innovation and process improvement is often unclear. Innovations typically involve more radical changes that significantly alter the process [16-18]. On the other hand, improvement focuses on the ongoing efforts of individuals involved in processes, aiming to enhance their performance. Improving the entire process chain as an integrated system of activities centers around value stream mapping, which is the main subject of the following case study [19,20].

3 Methodology

3.1 Workplace spatial arrangement

The layout, or spatial arrangement, of the workplace plays a crucial role in determining the overall efficiency of a company. It involves organizing production departments, workstations, tools, machines, and other essential equipment, with a focus on optimizing the movement of work [10]. The most critical aspect of this arrangement is the strategic and effective placement of production equipment to ensure that employees have the best possible conditions for performing their tasks efficiently. A well-designed layout impacts the entire production flow, influencing production costs, particularly those associated with material handling and transportation. Finding the optimal workplace layout is complex and challenging, but it is vital for enhancing production efficiency [21-24].

Poor allocation and arrangement of production facilities lead to inefficient logistics, longer material flows, increased transport times, and a greater need for intermediate storage (buffers) for materials, semi-finished goods, and finished products [23-25]. These issues collectively drive-up production costs. Efficient allocation and layout aim to integrate capacity, material, economic, safety, and technological factors while minimizing subjective decision-making in the placement and configuration of workspaces and production facilities. Addressing these challenges requires a project-oriented approach grounded in key logistics principles such as systems thinking, algorithmic planning, coordination, and global optimization [22].

3.2 Layout of the new production hall

The new production hall being developed in the industrial zone of the Kosice district Nad Jazerom will have approximate dimensions of 90 meters by 60 meters. Unlike the existing production facility on South Avenue, the entire production process in this new hall will be carried out on a single floor, where all products will be manufactured. The layout design of the new production hall is illustrated in Figure 1.

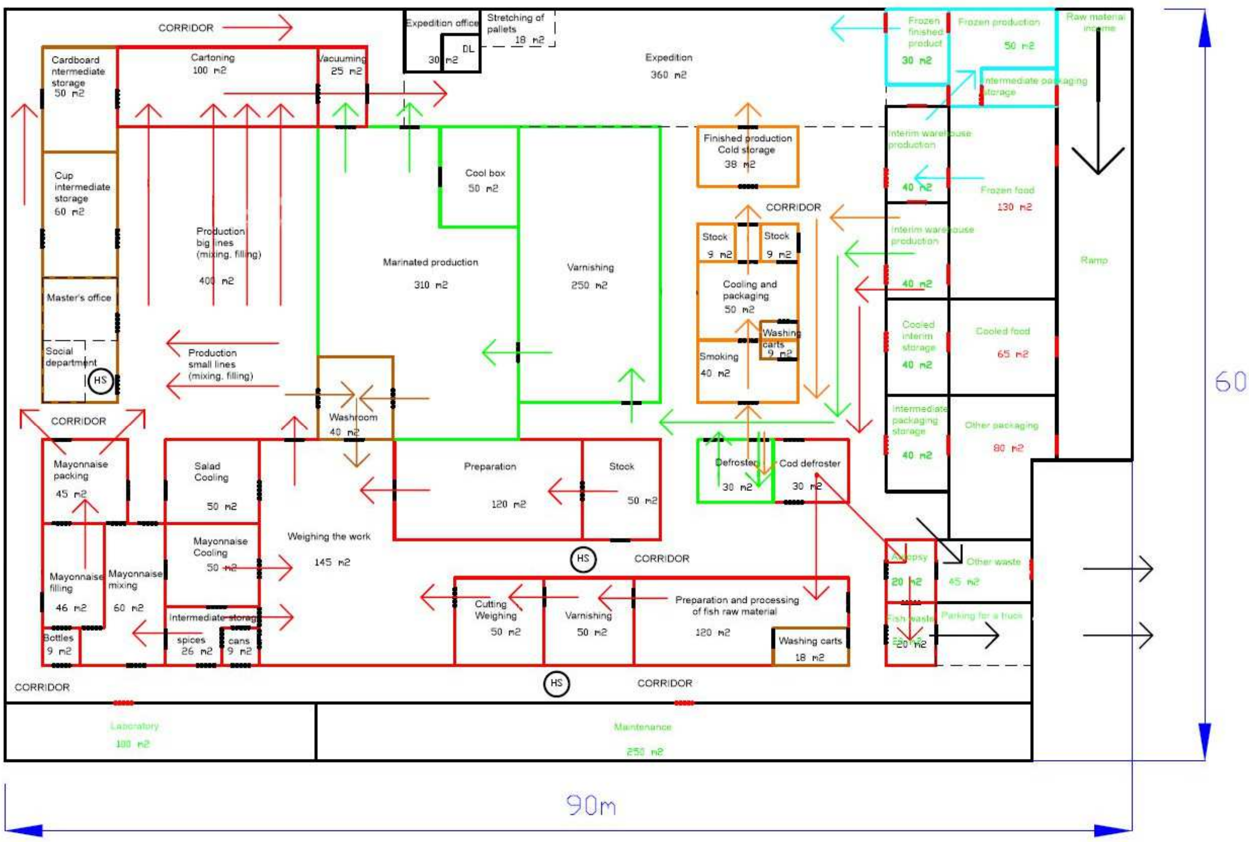

Figure 1 Layout and material flow in the new production facility

The picture (Figure 1) also shows the material flow of each production. Each color of the arrows represents a different material flow.

---> **Frozen production** ---> **Smoked production** ---> **Production of fish products**
---> **Marinated production** ---> **Garbage** ---> **Containers**

3.3 Material flow for a specific fish product

The material flow for producing a specific fish product begins with the receipt of frozen fish raw material in the warehouse, where it must first be removed from its transport packaging. The required amount for daily consumption is then moved to the intermediate storage. The initial step in the process is thawing the fish. Once the appropriate time has passed, the thawed fish is taken out of its packaging, and its quality is checked during unpacking. The inspected raw material is then transferred to the next production stage, which involves cooking. After cooking for the designated time, the fish is ready to be cooled. Following the cooking and cooling stages, the fish is marinated. Once marination is complete, the fish is ground and weighed. Meanwhile, sterilized vegetables and other necessary ingredients are prepared and weighed. These ingredients are then combined with mayonnaise. The mixture, precisely weighed and prepared, is then processed in a new fully automated line designed for fish product production. This line handles jar filling, packaging, cartoning, and stacking of the cartons onto pallets, with conveyors aiding the process. Finally, the prepared pallet is wrapped in stretch film and made ready for dispatch to the logistics distribution warehouse.

Figure 2 and Figure 3 illustrate the material flow for producing this specific fish product, with red arrows indicating the product flow and black arrows showing the waste flow. Figure 2 specifically depicts the material flow for the preparation of the fish raw material.

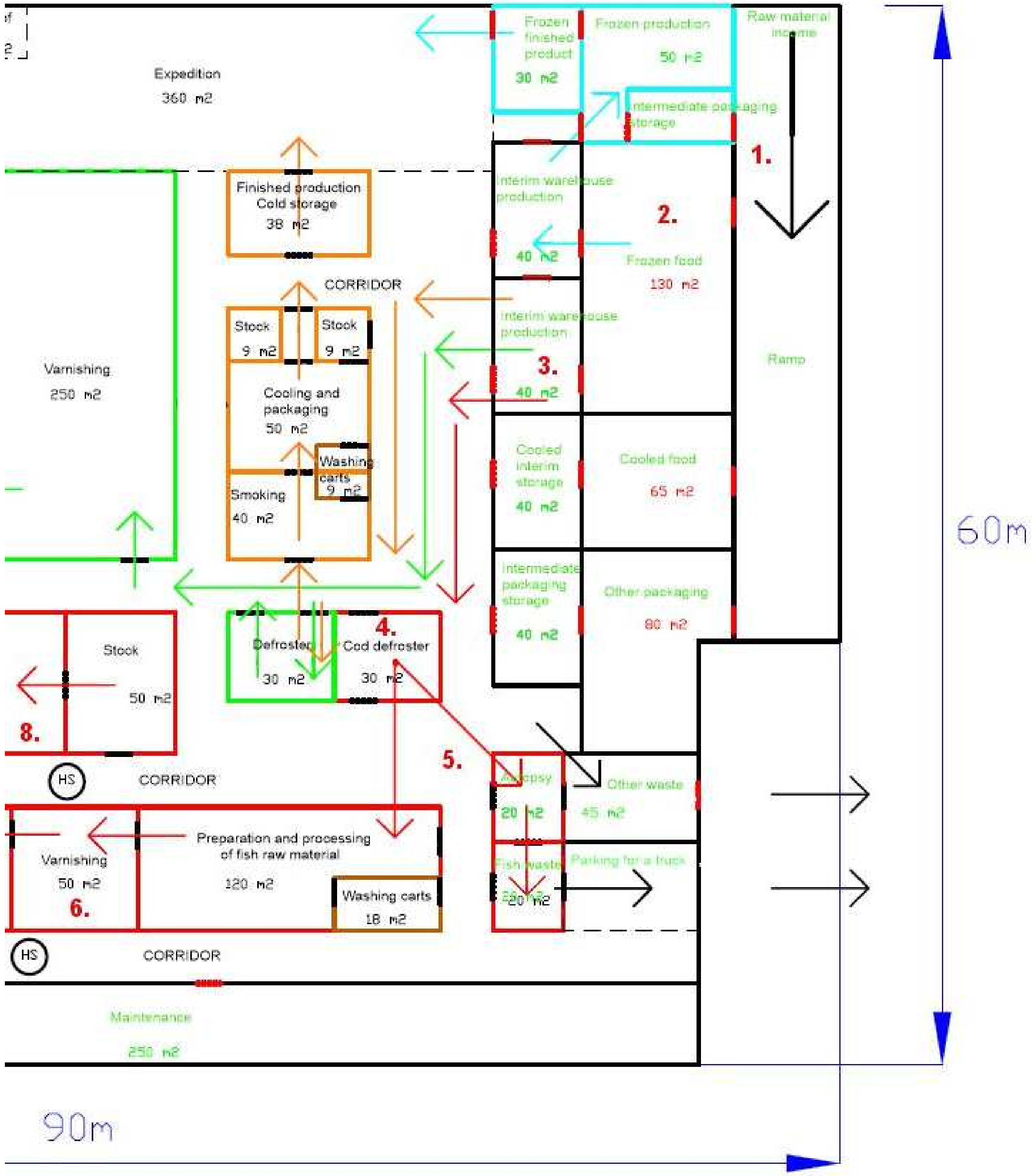

Figure 2 Material flow for producing a specific fish product – 1

Figure 3 illustrates the material flow for weighing, product manufacturing, packaging, cartoning, and the final step of shipment.

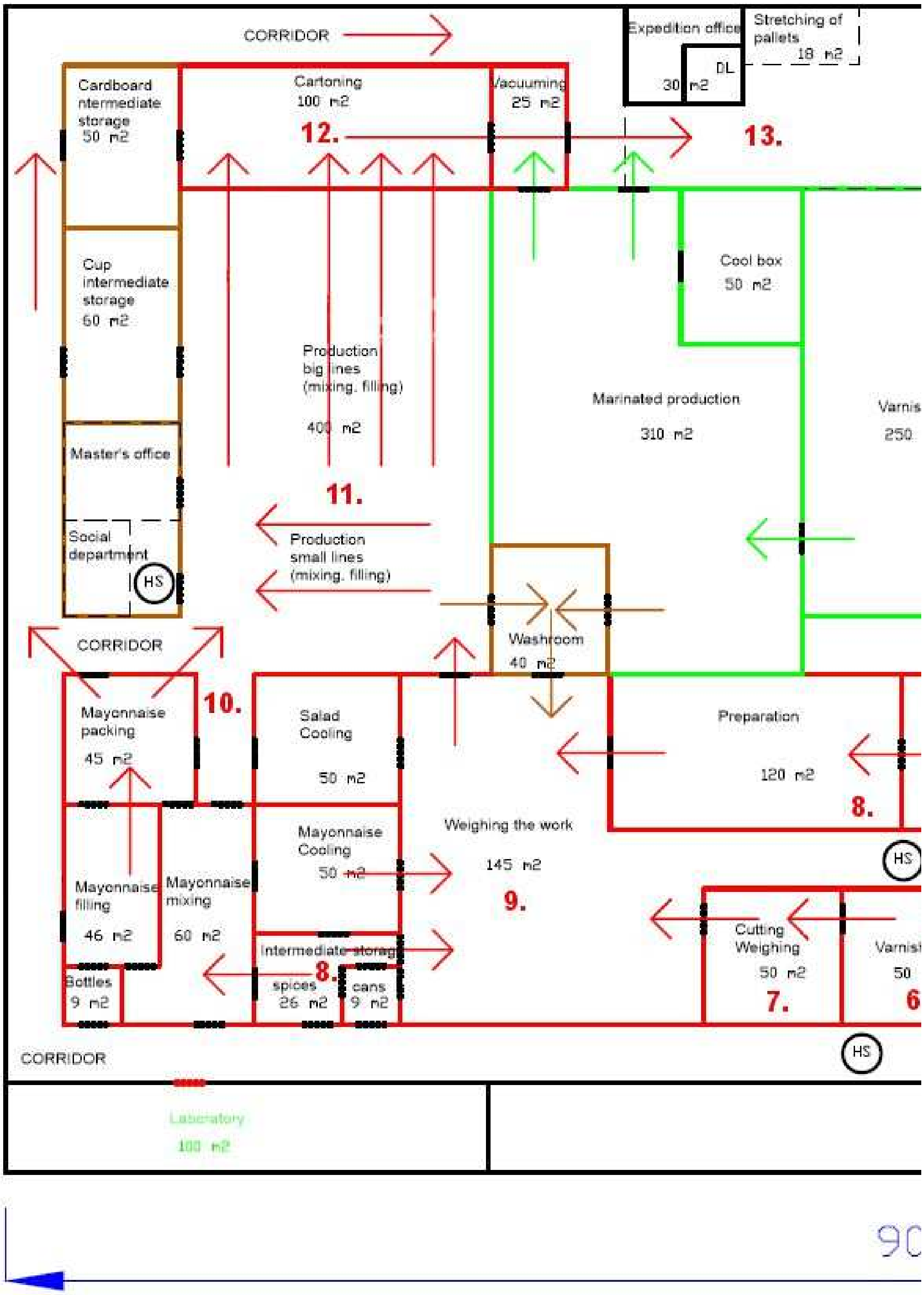

Figure 3 Material flow for producing a specific fish product – 2

The legend:
1. Intake of fish raw material,
2. Store of frozen raw materials,
3. Interim warehouse production,
4. Defrosting,
5. Preparation and processing of fish raw materials (dissection, cooking, cooling),
6. Painting,
7. Cutting and weighing,
8. Preparation of vegetables and ingredients,
9. Weighing,
10. Adding mayonnaise,
11. Production of cod or fish salads (mixing, filling),
12. Cartooning,
13. Shipping of packed pallets with the finished product.

3.4 Predictive production simulation

Using the Tecnomatix Plant Simulation software, we will simulate the predictive production of Treskoslovak Cod in mayonnaise and Paris salad. Using the 3D function in TX Plant Simulation, perimeter walls, and partitions will be modeled according to the layout so that we can better imagine how the newly emerging production plant RYBA Košice will look like. The duration of the simulation will be set to 8 hours, exactly as one work shift will last. Based on this simulation, we will find out the estimated number of pallets of Treslovakian cod in mayonnaise and Paris salad that could be produced in 8 hours.

3.4.1 Predictive simulation of the production process of Treskoslovak Cod

The simulation of the production process for Treslovakian Cod in mayonnaise excludes certain time intervals, as the entire production process spans roughly three days. However, a more precise estimate for the duration of the full production process for Treslovakian Cod in mayonnaise is about 48 hours.

The simulation begins with the receipt of the fish raw material and its unpacking from the transport packaging, but the processing time for this step is set to zero in the simulation. Similarly, the time required for moving the material to the warehouse and then transferring the fish to the daily intermediate storage is not considered. Additionally, the time needed for thawing the frozen fish raw material is also excluded. Although the thawing process is expected to take around 8 hours, it is still under refinement, with the goal of reducing it to less than 8 hours.

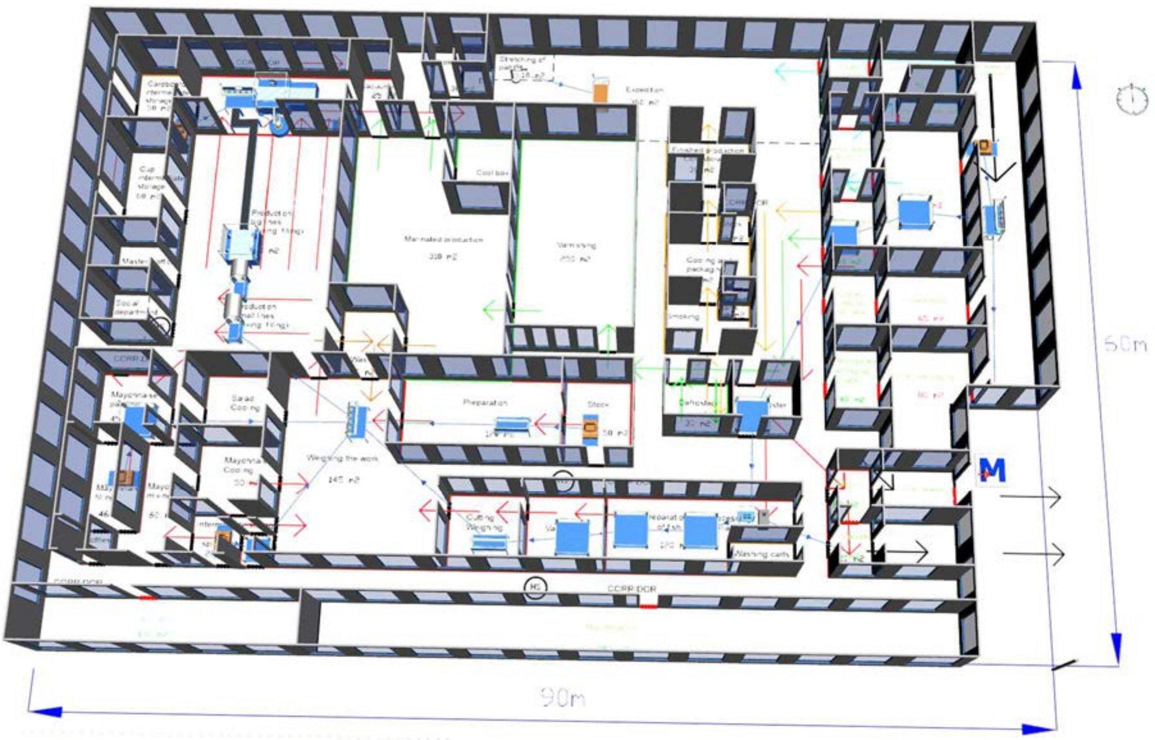

Figure 4 3D model of the production process of Treskoslovak Cod

After thawing, the fish raw material is unpacked and subjected to a quality check, although the time for these steps is not included in the simulation. Following the unpacking and inspection, the fish is cooked and cooled, but these durations are also set to zero in the simulation. The cooking process is expected to take up to an hour and a half, and the cooling process the same. Once the fish is cooked and cooled, it proceeds to the marination stage. The marination process, which actually takes 12 hours, is also set to zero in the simulation. The next step is grinding the fish, marking the first process where time is accounted for in the simulation. While the fish is being ground, the necessary ingredients and additional raw materials for producing Treslovakian Cod are prepared and weighed. The weighed mixture is then transferred to a new fully automated line that handles bag folding, mixing, filling, labeling, foreign object inspection, packing, cartoning, and palletizing. Once the pallet is full, it is wrapped in stretch film, making it ready for shipment.

For a clearer understanding of the Treslovakian Cod production process and a visualization of the production hall, a 3D model created using TX Plant Simulation software is shown in Figure 4. If only Treslovakian Cod in mayonnaise is produced during a given shift, approximately 11 pallets can be completed.

3.4.2 Predictive simulation of the Paris salad production process

The simulation of the Paris salad production process does not account for the time spent receiving the raw materials. These materials will be delivered to the warehouse and unpacked from the transport packaging continuously, rather than on the day the salad is produced.

Once the raw materials are received in the warehouse, with the time set to zero, the production process begins with the preparation of salami, marking the first stage where time is included in the simulation. The salami must first be unwrapped, then sliced to the required dimensions. The sliced salami is then marinated for 2 hours. During this time, the vegetables and other necessary ingredients for the Paris salad are prepared.

When the salami is painted, all the ingredients are weighed. The mixture weighed in this way will be moved to the new fully automatic line. On this line, mixing, transfer of the mixed mixture to the container, filling into jars, labeling, inspection of foreign objects, cartoning and finally storage on a pallet will take place. A pallet filled in this way according to the required parameters is just wrapped with stretch film and is ready for dispatch.

For a better visualization of the Paris salad production process, we can see a 3D model from the TX Plant Simulation software in Figure 5.

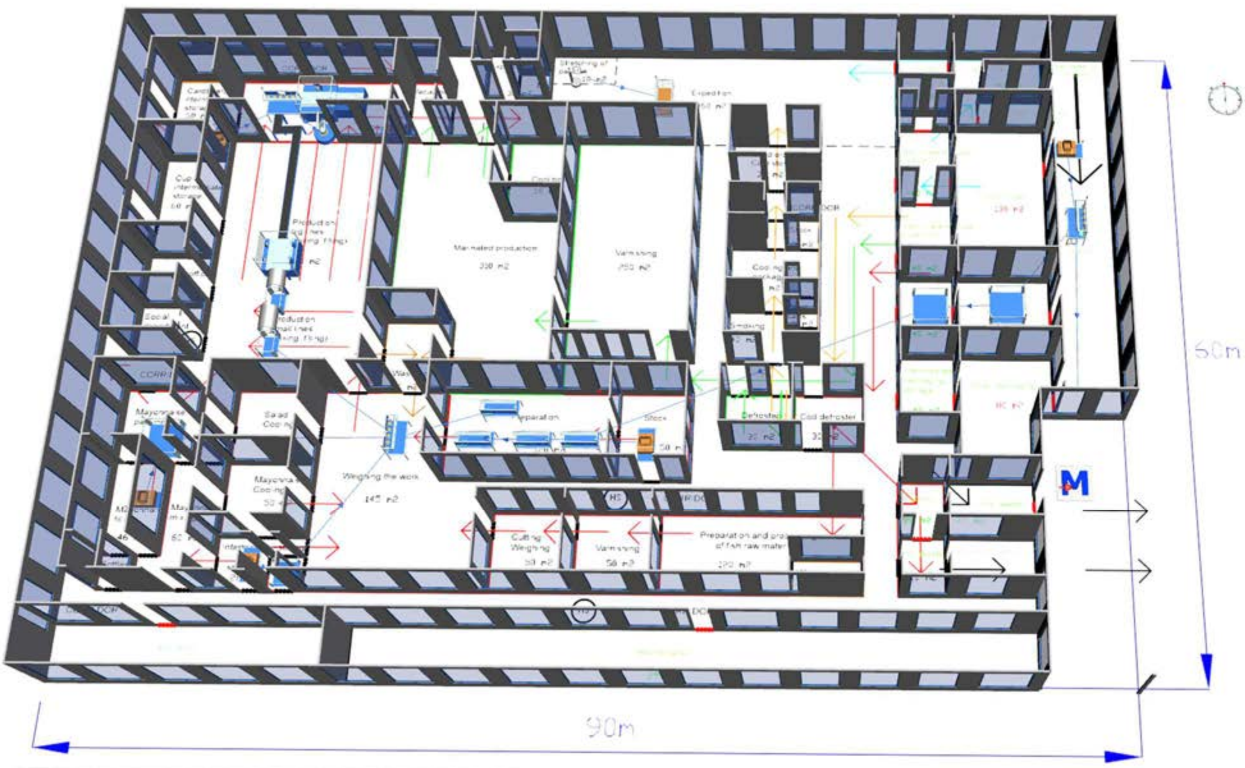

Figure 5 3D model of the Paris salad production process

Based on the predictive simulation of the production process of the Paris salad, which would be produced during the entire 8-hour work shift, approximately 5 pallets could be produced and packed.

4 Results and discussion

4.1 Evaluation of the current and emerging layout

A key advantage of the layout design for the new RYBA Kosice production facility is that the entire production process will be conducted on a single floor. Currently, production is spread across two floors, creating bottlenecks and inefficiencies as part of the process begins on one floor and is completed on the second floor.

Another big advantage will be that the plant being prepared for construction will be completely new. We will be able to implement new fully automatic lines, conveyors, and other new technological devices. Based on the dimensions of the new technological equipment, and predictive simulations, we can create a perfect layout solution for the operation, where partitions and the location of machines will be designed exactly so that production is as efficient as possible and no bottlenecks arise during the production process.

4.2 Evaluation of predictive manufacturing

Initially, the results of the production process for Treskoslovak Cod in mayonnaise will be assessed. In both scenarios, the simulation duration is set to 8 hours. Also, placing packed cartons with products on the pallet is the same as in the simulation, with which the results will be compared.

Figure 6 shows the outcome of the predictive production for Treskoslovak Cod in mayonnaise at the new RYBA Kosice production facility.

.Models.Predictive_production

Simulation time:8:00:00.0000

Object	Name	Mean Life Time	Throughput	TPH	Production	Transport	Storage	Value added	Portion
Finished_product	Pallete_of_product	1:22:06.7918	11	1	47.94%	52.06%	0.00%	0.04%	

Cumulated Statistics of the Parts which the Drain Deleted

Figure 6 The result of the predictive production of Treskoslovak Cod

Based on the results, it is apparent that the new production hall could produce 11 pallets of Treskoslovak Cod in mayonnaise, which is an increase of 5 pallets compared to the current output. However, this simulation result is merely predictive and may vary slightly from actual outcomes. The simulation used estimated times for some production tasks, and actual production might be influenced by technical issues or other unforeseen factors. The purpose of the simulation was to evaluate the potential production capacity of the new line, acknowledging that multiple types of Cod will be produced in each shift, not just one. Additionally, it is noted that 47.94% of the total time is spent on production processes, while 52.06% is dedicated to transportation. These results suggest that the proposed layout may not be optimal, prompting further investigation to achieve the most efficient configuration.

Next, the results of the Paris salad production process will be analyzed. In this case as well, the simulation duration is set to 8 hours, and the storage of packed cartons on the pallet remains consistent.

Figure 7 displays the results of the predictive production of Paris salad at the new RYBA Kosice production facility.

.Models.Predictive_productio_of_Paris_salad

Simulation time:8:00:00.0000

Object	Name	Mean Life Time	Throughput	TPH	Production	Transport	Storage	Value added	Portion
Expedition	Paris_salad	2:59:17.9403	5	1	46.38%	53.62%	0.00%	0.02%	

Cumulated Statistics of the Parts which the Drain Deleted

Figure 7 The result of the predictive production of the Paris salad

The simulation results indicate that roughly 5 pallets of Paris salad could be produced and packed in a single work shift at the new production hall, which represents an increase of 2 pallets compared to current production levels. However, it is important to note that this simulation for Paris Salad production is only a predictive estimate. Some of the times that were used in the simulation are given only as an estimate, how long they will last in reality is not yet known exactly. Therefore, we can conclude that the result of the predictive simulation is not accurate and will differ from reality. It is also important to remind again, as with the cod production process, that during one shift, not only Paris salad is produced, but also other types of delicatessen salads. The simulation was conducted to assess the potential capacity of the new deli salad production line.

5 Conclusions

The advancement and streamlining of processes within industrial and logistical contexts are increasingly recognized as crucial factors for organizations striving to attain a competitive edge and long-term success in the 21st century. Maximizing efficiency in new operations largely depends on an effective layout design and streamlined material flow. These essential factors can be effectively achieved through the use of industrial engineering techniques.

The analysis of statistical data from the Tecnomatix Plant Simulation software shows that the production process in the production hall will be more efficient, to a large extent the specific places that arose during production will be eliminated. The simulation results provide a clear indication of the potential improvements in workflow and productivity, demonstrating the tangible benefits of an optimized layout and material flow.

In conclusion, it is very important to remember that it is not yet possible to say exactly how much production will be more efficient, since the predictions were predictive due to missing some data and times, which in the simulation were given only as approximate estimates after discussion. This inherent uncertainty highlights the need for continuous monitoring and adjustment as actual data becomes available during real-world operations.

Our forthcoming research endeavors will focus on further enhancing both layout and material flow. All modifications will undergo systematic verification through simulation experiments to ensure their efficacy and feasibility. We will persist in employing industrial engineering methods throughout these adjustments, continuously seeking to refine and improve our processes. By doing so, we aim to develop a robust framework that can adapt to evolving production requirements and technological advancements, ultimately contributing to sustained operational excellence and competitive advantage.

Moreover, future studies will consider integrating more advanced predictive analytics and real-time data collection to refine simulation accuracy. This will allow for more precise adjustments and provide deeper insights into the dynamic nature of production environments. Our commitment to leveraging cutting-edge technologies and methodologies will remain steadfast as we strive to optimize our production processes further.

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Planning of flexible manufacturing lines with AGV material handling for the entire life cycle

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Keywords: AGV, simulation, battery degradation, FMS.

Abstract: The article is related to recent research focusing on the design of flexible manufacturing systems. It is not possible to design a flexible production system without planning the related logistics, material flow and its management. A key component of flexible manufacturing systems is material handling systems, which are often means using AGVs to transfer parts from station to station. With the increasing prevalence of the advanced control logics and artificial intelligence, AGV is poised to become a fundamental element of many production lines and logistics operations. Many studies focus on how many AGVs are needed for a given production line or logistics area. However, those papers do not deal with the effect of battery degradation during the life cycle of the production line or logistics area. During this period the battery of these devices degrades and thus their capacity is significantly reduced. The article explains how discrete event-based simulation can support the planning of AGV-based systems, particularly analysing the impact of AGV battery degradation during the life cycle of a flexible manufacturing system. The result of this article is a general methodology that is suitable for determining the required number of AGV units for the entire life cycle of a given production site or logistics activity.

1 Introduction

A very exciting period of transformation of production processes is taking place these days. Customer needs are changing significantly, customers want to buy more and more unique and customized products [1]. Accordingly, manufacturing companies must also transform from the former mass production to flexible production [2]. This change happens so dynamically that in many cases there are no developed methods and practices for creating production lines and production processes that meet the needs. Important factor is that flexible production usually requires more flexible and therefore significantly more expensive equipment, therefore it is realistic for manufacturing companies to expect that this equipment can be used for a longer period [2]. It means that the life cycle of flexible production lines getting longer. In this article, we examine the life cycle of flexible production systems and production lines and its elements. In the second part of the article, the AGV (Automated Guided Vehicle), one of the most common material handling devices in flexible production systems, is examined from a design point of view. Finally, we analyse an example how the development of the capacity of AGVs during the life cycle of the production line can be considered with digital tools.

2 Literature review

Production systems produce products, so understandably their life cycle cannot be separated from the life cycle of the product manufactured on them. In fact, the production line is also a product, so its life cycle is characterized by everything that is characteristic of a product's life cycle [1], although the names of the phases are closer to the terms used in production (Figure 1).

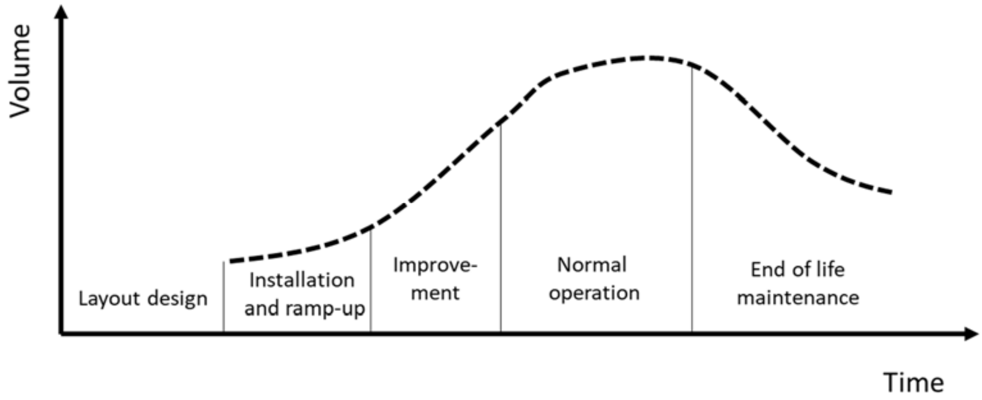

Figure 1 Lifecycle of a production line [3]

In the case of production lines, the design phase has changed a lot over the years. In addition to the existence of many manual methods for planning production lines [4-6], the increase in the complexity of production processes required the introduction of new methods. One of the most widespread methods is the construction of a digital twin of the production line and conducting experiments to find the appropriate operating parameters.

Table 1 summarizes what the digital twin can be used for in the different life cycle steps of the production line.

Table 1 Lifecycle steps and use cases of the Digital Twin during the lifecycle steps

Lifecycle step	**Use cases for a Digital Twin**
Layout design	Process planning (manufacturing and logistics) Capacity planning Resource planning (number of machines, palettes, AGVs, etc.) Line balancing Cost/investment optimization
Installation and ramp-up	Ramp-up analysis Virtual commissioning
Improvement	Bottleneck analysis System parameter optimization Update of process parameters from real world Energy efficiency optimization
Normal operation	Further optimisation of the system Operational support for the shop floor New product introductions (NPI)
End of life maintenance	Maintenance planning

3 Conceptual framework

The basic purpose of flexible manufacturing systems is to ensure the production of different products within the same system. Flexible production systems can produce products that are even significantly different from each other if their technological steps and needs are similar. Another typical purpose of flexible production systems is to support the customization of products during production [3].

Most flexible manufacturing systems consist of the following 3 main elements [7]:

- Work machines, which can be machining or any other processing machines.
- The material handling system, which, depending on the design, can be conveyor or AGV-based material handling system.
- The control system, whose task is to operate the system in changing conditions, controlling both the working machines and the material handling system.

In terms of layout, 4 main types can be distinguished [7,8], these are as follows:

- In-line layout,
- Loop layout,
- Ladder layout,
- Open-Field layout.

Their schematic diagram is shown in Figure 2.

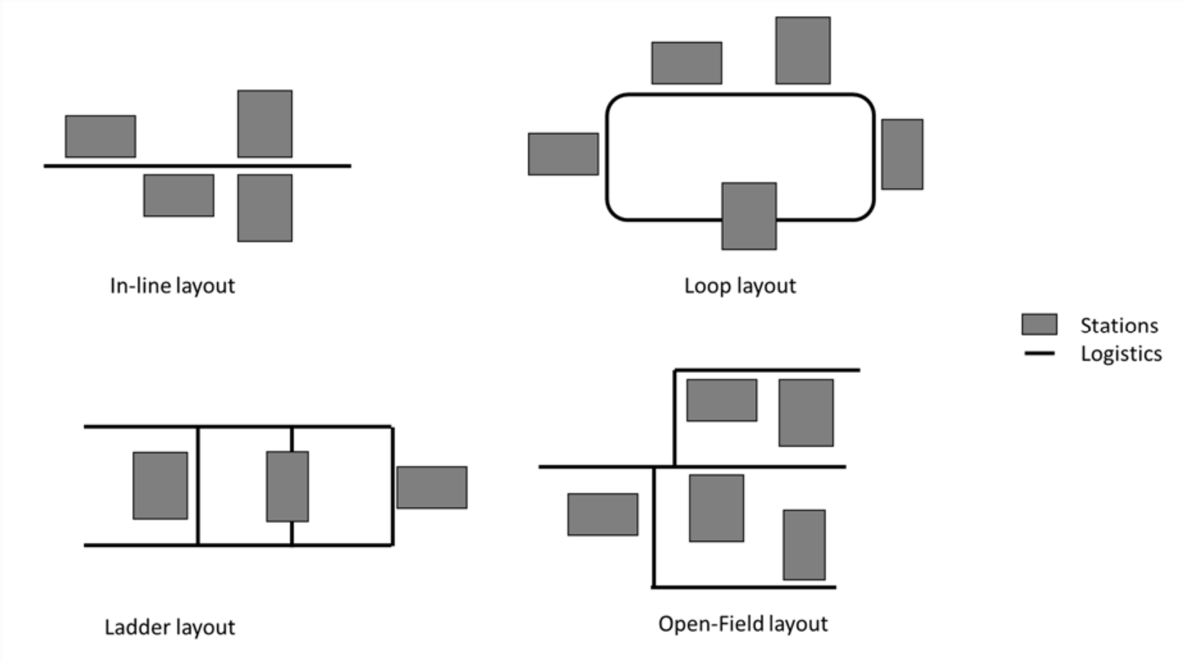

Figure 2 Types of the Flexible Manufacturing Systems [7]

In the case of Loop, Ladder and Open Field layouts, material handling is solved either with conveyor systems or often with AGVs. There are several advantages and disadvantages of AGVs compared to conveyor-based material handling (Table 2)

Table 2 Advantages and disadvantages of using AGVs

Advantages	**Disadvantages**
Flexible material handling	Although the price of the technology is falling, the price of the battery limits further significant price reductions
It helps to make the surrounding production system more flexible	A more advanced IT environment is required for its control
It enables good material flow control	Due to the battery, the environmental impact is higher
The layout they serve is easily to modify	Due to the charging cycle, a complex control system is required for their best utilization
Easily replaceable in case of failure or breakdown	
Easy maintenance	
Flexible and adaptive control can be built around it	

From the table above, most of the disadvantages of AGVs (price, more complex control, etc.) are due to the nature of the battery, so it is worth examining this topic in more depth. Older AGVs mainly use Lithium-ion batteries, which have a lifetime of about 2000 charging cycles [9]. In the modern AGVs Lithium-titanium (LTO) batteries are typically used [10]. These batteries have a very serious life cycle, they can withstand approximately 20,000 charge cycles [11,12].

Currently, there is relatively little long-term experience with AGV battery degradation, so we had to rely on the (sometimes admittedly optimistic) specifications provided by manufacturers. However, it is clear [6] that after approximately 4,000 charging cycles these batteries can already suffer a significant capacity reduction of more than 15% (Figure 3).

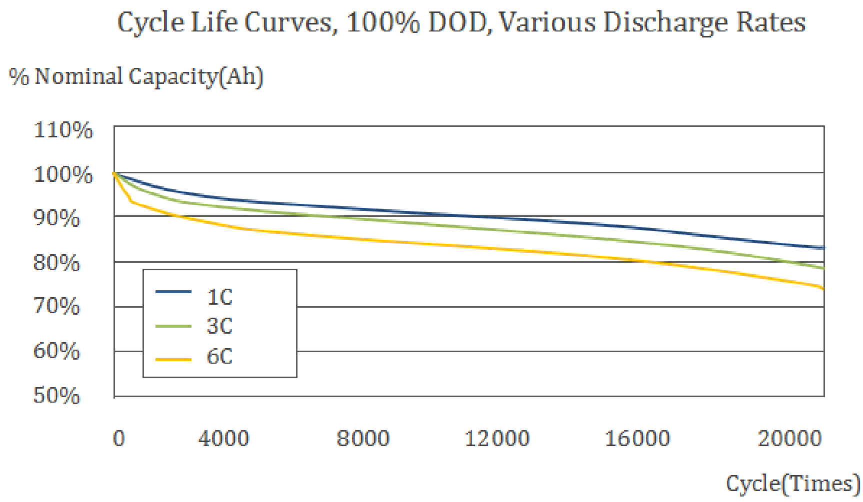

Figure 3 Degradation of the LTO batteries over the time [10,13]

Apart from degradation there are several additional factors that affect the lifetime and behaviour of battery powered AGVs [13]:

- Operating temperature – this can reduce capacity by 5-10% in extreme cases [13],
- Number of charging cycles,
- Depth of Discharge (DoD),
- Storage time,
- Number of starts and stops during the operation,
- Weight of the transferred load.

The influencing effect of these can be determined mainly by experimentation and measurement.

In the case of AGVs, two main methods are used for recharging, battery swap and battery charge. In a production environment, the latter can be implemented and handled more simply, so we will deal with this in the following.

An average AGV can operate for 4 hours with one charge, followed by 1-2 hours of charging, so in the case of a three-shift production, it goes through 4 charging cycles per day, counting the minimum typical 200 working days, this is 800 cycles per year. This also means that approx. After 5 years, only approximately 90% of its original capacity can be used, and after another 5 years, this value may drop to 80-85%. In extreme cases (for example, AGVs which are carrying car bodies) the operational time between two charges is less than 2 hours, the charging time is 1 hour. In this case, for an AGV which works in 3 shifts every day, it has 8 charging cycles. It means that the battery degradation will have significant effect on the performance after just 2 years of usage.

4 Research methodology

During the research, we used a discrete event simulation system for the concept building and the analysis of the results [14,15]. Discrete event simulation is a reliable tool to analyse systems, where the eclapsed time is a critial factor [16,17]. We selected the Siemens Plant Simulation system to prepare the analyses. This discrete event simulation software is widely used by manufacturing companies [18,19]. The system also has the advantage of supporting the modelling of AGVs, and even has built-in functions to manage AGVs' battery-related characteristics and battery charging. Plant Simulation handles the following battery characteristics for AGVs [20] (Table 3) and collects the following statistical values from the simulation (Table 4).

Table 3 Battery related simulation attributes for AGVs

Attribute	**Description**
Charge (Ah)	The active charge of the battery (0 < Charge < Capacity)
Basic consumption (A)	Basic consumption no matter if the AGV is moving or not
Driving consumption (A)	Addition to the Basic consumption if the AGV drives
Capacity (Ah)	The capacity of the battery
Reserve (Ah)	Below this value the battery needs to be recharged, system calls the charge control
Charge current (A)	The value of the charging current

Table 4 Battery related statistical values collected by the simulation model

Attribute	**Description**
Number of Charges	Number of times the battery was charged
Portion	Portion of its life-span during which the battery of the AGV was charging

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During the modelling, AGVs can be either fixed-track or free-moving. Among the FMS layout types, the Loop and Ladder layouts usually have fixed tracks, while the Open field design uses freely moving AGVs.

The AGV energy consumption is can be calculated as follows (1):

$$Energy\ consumprion = Basic\ Consumption + Driving\ Consumption \quad (1)$$

where the driving consumption could depend on several factors, like the speed, the weight of the transferred part or the environmental temperature as we discussed before. These values can be determined by measurement or can be extracted from the logs of the control software of many AGVs.

5 Experimental analysis and presentation of the results

To analyse the previously discussed problem area, we used an example from the automotive industry. Figure 4 shows the model and its layout. It is a flexible production system with a loop layout, with robotic welding and automatic assembly stations. The products are car body parts. The line is designed for a life cycle of at least 10 years. The factory works in 3 shifts in 7 days.

During the test, we are now testing the system for one product type, assuming that:

- The production times of the products at the stations are very similar.
- There is no setup between products at the stations (except the test station).

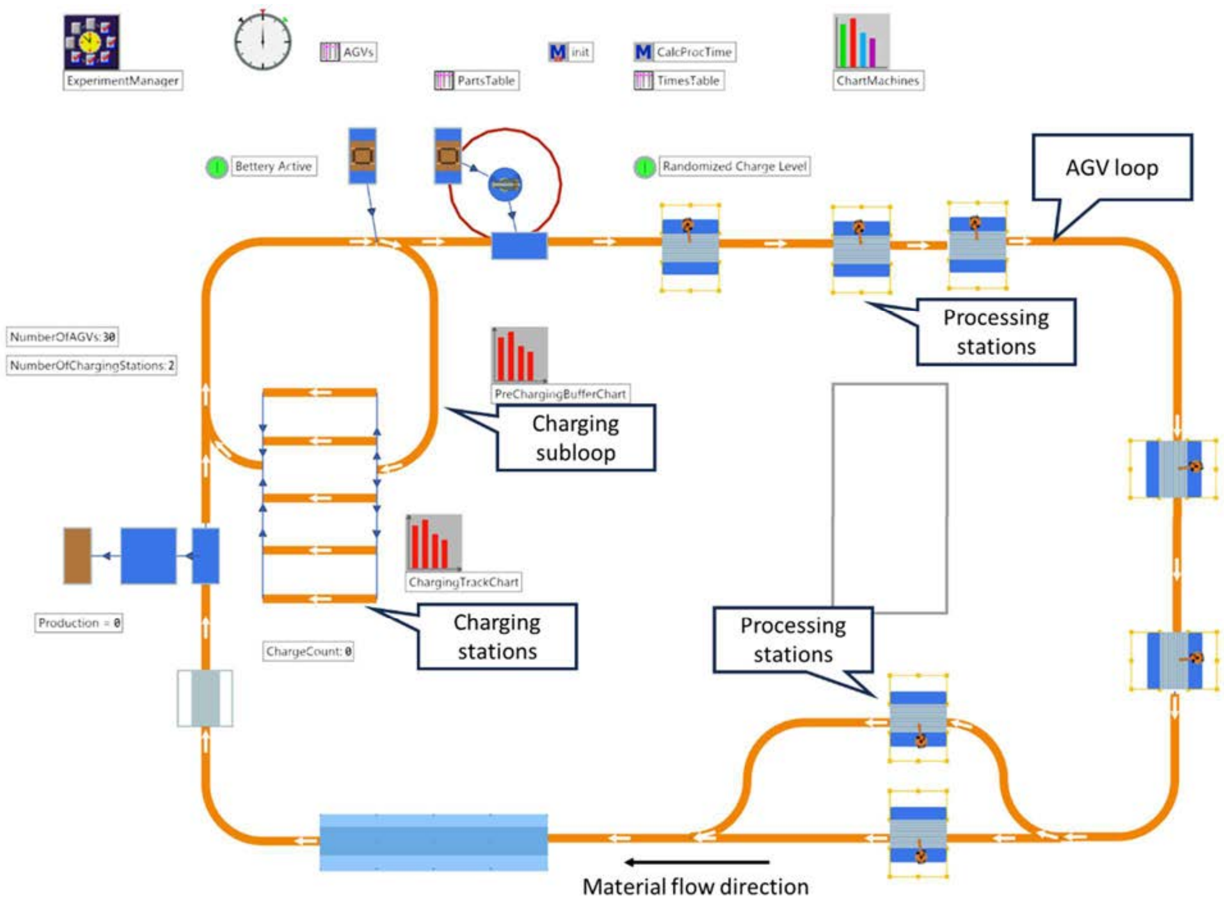


Figure 4 The layout of the experimental model

In the example we use SHARP TYPE B AGVs in the simulation model [21] with load capacity of 200 kg, 60 m/min (1 m/s) maximum speed, and 2 series of 42 Ah batteries. The assumed hours of operation for this AGVs are 8 hours, so they can theoretically serve a whole shift without the need of recharge.

During the modelling, we wanted to visualize the battery level, hence we extended the AGV object with the colouring of the loading plate depending on the battery level (Figure 5).

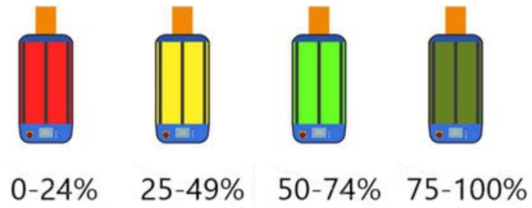


Figure 5 Colour coding of the AGVs based on the available battery capacity

As a result, the charge status of each AGV is clearly visible in the model (Figure 6), making the analysis and understanding of the digital twin easier.

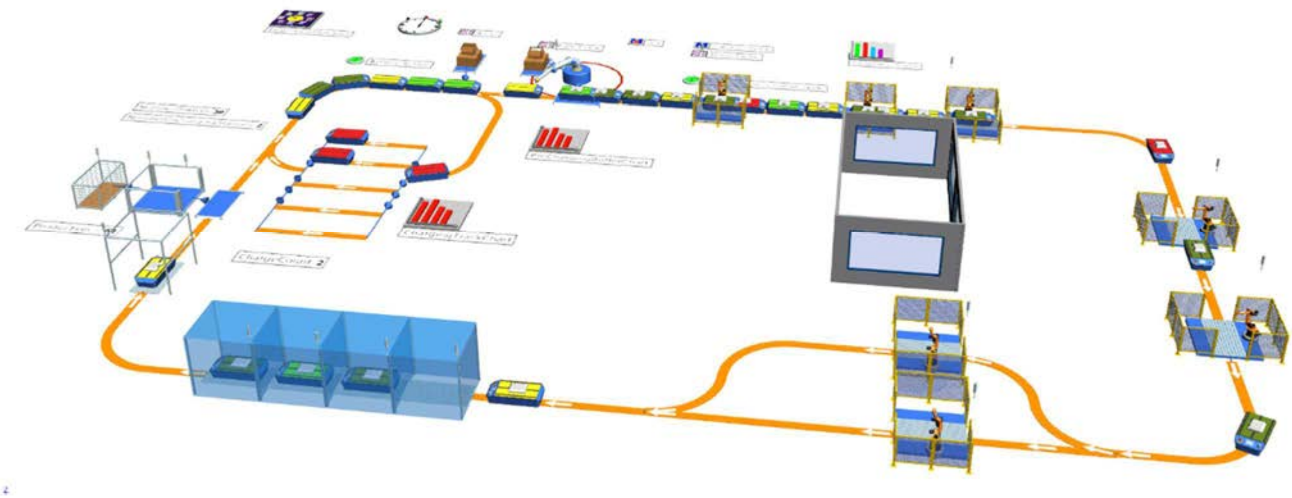


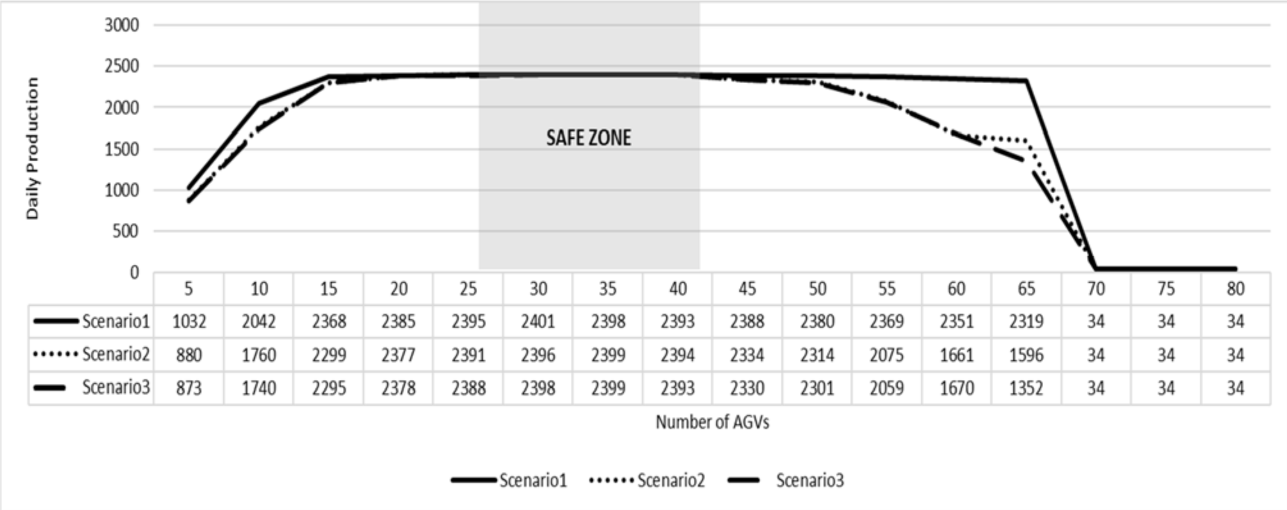
Figure 6 Model run with the coloured AGV battery states

We developed a 3-step planning process for system modelling and analysis (Table 5).

Table 5 Steps for the system planning and analysis

Process Step	**Comment**
1. Calculation of the necessary AGV capacity	Run simulation experiments with full capacity AGVs with unlimited battery
2. Calculations and experiments with the actual AGV fleet	Finding design issues, calculation of the number of the necessary charging stations. This step also gives information for the programming of the AGV fleet control software (normally supplied by the AGV manufacturer)
3. Experiments with the future planned changes of the line, products and AGVs	Could include experiments about the AGV degradation and other parameters which will likely change during the lifecycle of the production area

The purpose of the first experiment is to determine the number of AGV units required continuously in normal operation. In the model this is done in an "ideal" environment, where the AGV battery usage is not simulated. However, all stochastic parameters of the line are included in the study (machine failures, etc.) (Scenario 1). In the second step, the effect of battery degradation and recharging of the AGVs is analysed. This tells how many AGVs are realistically needed on the production line. Here we can also determine how many charging points are required (Scenario 2). And the final, third step is to examine how many AGVs are needed later in the lifecycle of the production line. At that time the degradation of the AGV batteries is significant. In this step the number of required charging stations may also change, as AGVs in worse condition require more frequent charging (Scenario 3).



	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
Scenario1	1032	2042	2368	2385	2395	2401	2398	2393	2388	2380	2369	2351	2319	34	34	34
Scenario2	880	1760	2299	2377	2391	2396	2399	2394	2334	2314	2075	1661	1596	34	34	34
Scenario3	873	1740	2295	2378	2388	2398	2399	2393	2330	2301	2059	1670	1352	34	34	34

Figure 7 The daily throughput depending on the number of AGVs

Based on the graphical representation of the results (Figure 7), the following conclusions can be drawn. Clearly, too few AGVs result in very low productivity, and too many AGVs obstruct each other, so the number of produced units is drastically reduced. This is typical behaviour of all logistics systems where the material handling is managed with pallets or AGVs. In the first case, the number of produced parts decreases due to waiting for, and in the second case, due to blocking of material handling devices.

It can be clearly seen that, by plotting the results of all three cases, the AGV number between 30-40 ensures the maximum number of manufactured pieces in all three cases.

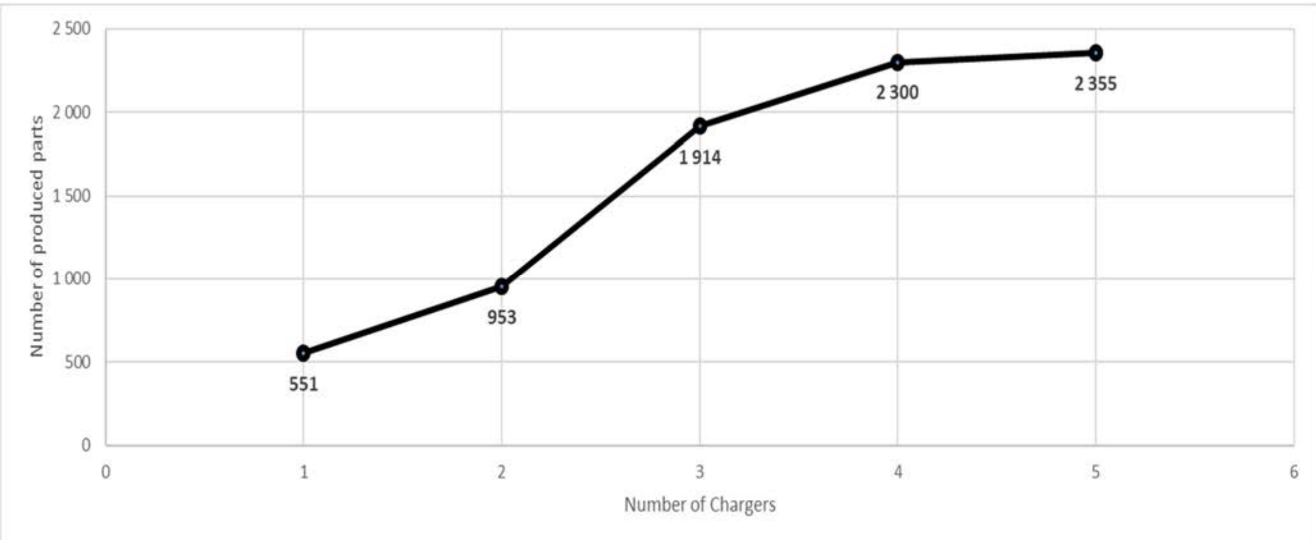


Figure 8 Results of the simulation of the necessary charging station number (AGV number is fixed, 35)

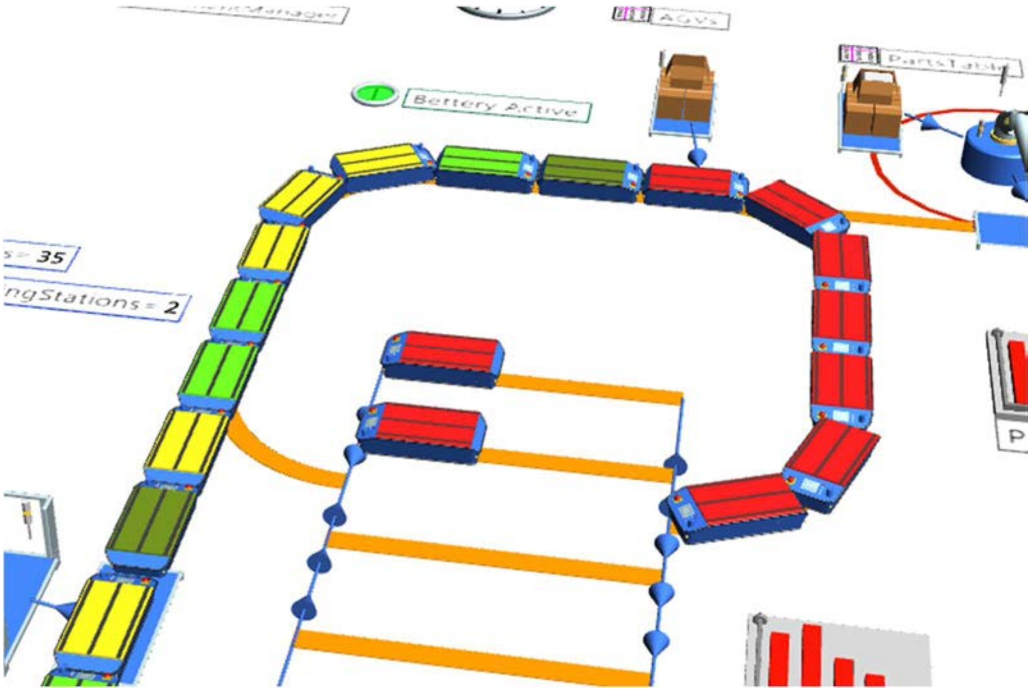


Figure 9 Blocking issues within the charging subloop

Using the above results, a further study was carried out to determine the required number of recharge stations. The result of it is shown in Figure 8. In the case if we have 1, 2 or 3 charging stations, the reason of the low number of produced parts was a layout problem. That is clearly visible in the simulation (Figure 9):

- The AGV charging subloop is congested and this loop is practically blocked, along with the main production circuit. This can be handled by expanding the length of charging subloop in the layout.
- By increasing the size of the charging subloop, another problem arises, that if too many AGVs are waiting in line for charging, it may happen that by the time the AGV gets to the charger, it will run out the power while waiting. This shows how important it is for the AGV to properly set the reserve level at which the AGV already starts towards the charging loop in the branch.

6 Conclusions

Apparently, within the design of flexible production systems, the implementation of material handling tasks with AGVs is a complex problem. The above article showed why it is not enough to simply determine the number of AGV units required to ramp-up the line. The degradation of batteries during the life cycle of the production line and having AGVs with batteries of different capacities in the production process represent a serious control and capacity planning task and challenge. During the research, we developed a simulation framework that is suitable for examining various AGV-based logistics processes and analysing the life cycle of AGVs. The simulation-based digital twin, constantly updated with current data (battery status, etc.), is suitable for providing support in determining the appropriate operating parameters during the operation of the actual production line. Since more and more research is being done on battery life, my future research direction may be a more accurate description of the degradation process in the digital twin. The advantage of simulation in this case will be that any mathematical model can be incorporated into the system. This mathematical model can consider the main AGV degradation parameters, such as the nature of the charging cycles, the operating temperature and the weight of the transported pieces.

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Integrating evolving customer preferences into green supplier selection: a hybrid model integrating Markov chain and fuzzy MCDM

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Keywords: Markov chain, fuzzy MCDM, green supplier selection, customer preferences.
Abstract: With growing awareness of environmental issues and increasing regulatory pressure to reduce carbon footprints, organizations are being forced to integrate green practices into their procurement processes. In today's sustainability-driven business environment, it is now crucial to integrate changing customer preferences into the Green Supplier Selection (GSS) process. This enables companies to ensure customer satisfaction and loyalty and adapt to market fluctuations. Indeed, by understanding customer preferences, companies can choose suppliers who meet market expectations while complying with environmental standards. However, existing literature reveals a significant gap in considering changing customer preferences when evaluating suppliers. The variability of customer preferences over time and the uncertainty in the GSS process, including vagueness in expert judgment and insufficient data, add to the complexity of decision-making. The need for a comprehensive customer-based GSS model is therefore undeniable. To fill this gap, this paper aims to introduce an innovative hybrid GSS model. This model uses the Markov chain to track and predict the evolution in customer preferences over time, then applies an improved and simplified fuzzy BWM method to establish a connection between selection criteria and customer preferences. Next, the fuzzy TOPSIS method ranks suppliers. To validate the effectiveness of the proposed model, a real-life case study is conducted evaluating three Green Suppliers of an industrial company, completed by a comparative analysis to verify the results obtained. The aim of this study is to evaluate suppliers and identify the best one able to meet customer requirements while aligning with the company's economic and environmental objectives.

1 Introduction

In the current environmental context, integrating green practices into supply chain management has become a key criterion for enhancing the overall performance of the company and its brand image in the market, enabling it to differentiate itself from competitors [1]. This goal can be achieved by improving the supply chain and adopting new practices with a lesser environmental impact. As the supplier evaluation and selection process is of paramount importance [2] in supply chain management, particular attention must be paid to integrating environmental concerns into this process [3]. Green supplier selection (GSS) is one of the most important aspects of transitioning to a more environmentally-friendly supply chain. On the other hand, suppliers play a crucial role in the manufacturing process and directly influence the quality of the final product [4]. Additionally, customer satisfaction levels are heavily dependent on the quality of the end product they consume. In some cases, despite a company being well-advanced with a high level of technology, the final product it offers may fail to achieve the expected success. This can be attributed to an excessive focus on certain criteria that may not align with customer expectations, or to a poor market needs analysis or inadequate understanding of customer requirements [5]. This interplay between these two actors—supplier and consumer—underscores the importance of studying the relationship between supplier selection criteria and customer requirements. This interrelationship must not be neglected and should be thoroughly considered by researchers for a deeper understanding and well-informed decision-making [6-8]. The literature review shows that few studies have focused on customer needs when selecting suppliers, however in real-world situations, this problem is very comment and is very important to consider [5]. [7] proposed a model combining the use of MCDM techniques and the QFD model for GSS. The main aim of the proposed model is to clarify and explain the interaction relationships between customer requirements and supplier selection criteria. The proposed approach is structured around two main phases: the first is based on a combination of methods (DEMATEL and QFD) to obtain the final weights of the selection criteria, while taking into account customer requirements. Secondly, the COPRAS method is used to classify and rate suppliers. This studies highlight the central importance of customers in the evaluation of supply chains. However, a significant limitation of these studies is that they neglect the dynamic and evolving nature of customer requirements, as well as the uncertainty and the fuzziness associated with this decision-making processes.

The conventional method of discerning customer preferences involves gathering information through surveys and interviews [9]. However, this approach is no longer adequate as the information collected may not accurately reflect the real-time needs of the customer. Indeed. Customers tend to constantly change their preferences; they may easily alter their preferences after experiencing a product or service, or due to external influences. Few studies in the literature have paid attention to the fluctuation in customer preferences.

The variability in customer preferences over time and the uncertainty associated with GSS process, including vagueness and ambiguity in expert judgment, as well as insufficient available data, accentuates the complexity of this Decision-Making. Therefore, the main objective of this study is to support Decision-Makers by proposing a comprehensive model for GSS in an uncertain environment. This model considers both changing customer preferences and environmental factors, aiming to provide a holistic approach to supplier selection that addresses the challenges posed by uncertainty and evolving customer preferences. This model is based on the use of Markov chain in combination with two popular MCDM methods and fuzzy theory. To the best of our knowledge, no method combines Markov chain, the Fuzzy BWM and the Fuzzy TOPSIS method for assessing green suppliers in the current literature. Markov Chain in applied to track and predict changes in Customers' Preferences, the Fuzzy BWM is used to connect selection criteria with the customers' requirements and find their optimal weights and finally the Fuzzy TOPSIS is used to rank and prioritize green supplier alternatives. The proposed approach is validated by conduction a real-world case study and comparing the results with another existing GSS models.

The following are the major contributions of this research that distinguish it from other studies related to the same topic:

- To propose a decision-making tool combining the use of Markov chain, an Improved fuzzy BWM and Fuzzy TOPSIS methods for the evaluation and selection of green suppliers.
- The weight of each criterion is calculated while considering customer preferences in a fuzzy environment
- Taking into account the uncertainty associated with customer preferences involves tracking the evolution of these preferences and predicting a new model independent of the initial one.
- Dealing with uncertainty in both customer needs and expert judgment.
- This paper contributes to helping researchers and practitioners to choose more effective and suitable green supplier that best meets the requirements of the decision makers and satisfies the customer's desires.

The remainder of the paper is structured as follows: Section 2 presents the findings of the literature review, highlighting the most important studies conducted in this field of study. Section 3 is dedicated to describing the steps of the proposed approach. In Section 4, a case study is conducted to test the proposed approach, and the results are validated in Section 5 through a comparative study. The results are then, analyzed and discussed in Section 6, followed by a conclusion in Section 7.

2 Related works

In this section, a brief presentation of the findings from the literature review regarding the most common selection criteria and approaches proposed by the authors, as well as the importance of considering the customer's preferences in GSS Problems.

In the last decade, the literature on (GSS) has significantly increased, highlighting the growing importance of this field of study [2,10-12]. However, some studies have focused solely on assessing suppliers' environmental performance, thereby limiting the scope of their findings. [13] extended the (AHP) method under interval type-2 fuzzy environment and proposed a GSS model based on environmental criteria. This model was then applied in a real case study involving a home appliance manufacturer and the findings indicate that the criteria: green product, cleaner production, green design, and green package has a substantial positive impact on the performance of green suppliers. [12] proposed an integrated approach using fuzzy MCDMs to select green suppliers based on their green capabilities. The proposed model identified nine criteria which can assist decision-makers in distinguishing the key criteria for selecting strategic green suppliers. [14], in this work, authors proposed three-phase method to help Khouzestan Steel Company decision-makers assess their suppliers according to their green innovation ability, seven main criteria and thirty-eight environmental sub criteria were suggested, emphasizing ecological considerations. GSS is a complex decision, as it depends on various factors that can sometimes be contradictory. Indeed, prioritizing ecological criteria can be more costly than prioritizing conventional suppliers [15]. Finding a suitable supplier therefore involves reconciling economic and environmental objectives. Research has underlined the importance of considering both economic and ecological criteria when evaluating suppliers, to ensure informed and balanced decision-making [10]. In the literature, [16] proposed an integrated approach to develop a (GSS) model for the air-filter industry by focusing on both classic and green criteria. In this study, a modified two-phase fuzzy goal programming model is proposed to provide a solution satisfying the optimization of both classic and green supplier scores derived from the Intuitionistic Fuzzy TOPSIS. [2]'s study focused on the textile sector due to its significant environmental impact, highlighting the necessity of (GSS) for stakeholders. To address uncertainty in GSS, the study proposed an integrated model combining two (MCDM) methods, BWM and TODIM, within an enhanced fuzzy concept using Interval Type-2 Fuzzy Sets (IT2FSs). Recently, [17] introduces a novel approach to GSS for food business packaging operations. It offers a comprehensive set of key selection criteria derived from a literature review encompassing both green and traditional aspects. Suppliers are evaluated using the proposed Pythagorean Fuzzy TOPSIS method. As evident from the literature survey, the use of fuzzy theories is becoming increasingly widespread. This trend underscores the utility and effectiveness of this tool in addressing uncertainty and ambiguity within GSS problems leading to better-informed and more reliable decisions. We can therefore conclude that, although MCDMs have proven their effectiveness in solving multi-criteria problems, relying solely on these methods limits the findings. The current trend is to propose hybrid models combining different techniques in order to capitalize on the advantages of each [18-20]. In this paper we propose a hybrid model that combines the use of the Markov chain with two Fuzzy MCDM techniques.

In an increasingly demanding and sustainability-driven business landscape, integrating customer preferences into the GSS process is of paramount importance. This not only enables companies to meet increasingly stringent sustainability regulatory requirements but also strengthens their brand image and fosters customer loyalty. By understanding customer preferences, companies can choose suppliers that offer products that meet market expectations while adhering to environmental standards. However, the literature on this subject remains limited, with few studies specifically addressing the consideration of customer preferences in GSS. [5] is one of the leading authors to take customer attitudes into account in the supplier evaluation process. Authors proposed an integrated and innovative model based on the use of the SWARA and QFD method to weight supplier selection factors while giving greater importance to customer requirements, then the WASPAS method is applied to evaluate suppliers. In another study, [6] proposed an integrated approach for GSS by considering both customer and supplier criteria to investigate the influence of customer satisfaction indices on the supplier selection process. The author applied DEMATEL and QFD to weigh the decision criteria based on the importance given to customer requirements, and then applied COPRAS to classify and rate suppliers. In order to meet customer expectations, [21] proposed an integrated approach for GSS while considering both customer requirements and environmental performance criteria. The author utilized the combined (DEMATEL-QFD) method to examine the interrelations between customer requirements and supplier selection criteria. Subsequently, interval type-2 fuzzy AHP (IT2 FAHP) was applied to prioritize alternative suppliers. Later, [18] proposed a new customer-oriented approach to explore supplier relationship management in supply chains and identify suitable technical criteria for evaluating the organization's supply chain needs. The proposed model combines QFD and AHP to determine the weights of technical criteria, after which the suppliers are ranked using the simple additive weighting (SAW) method.

Most of the previously cited studies consider customer requirements as a constant parameter, which limits the results of their research. In reality, human beings tend to constantly modify their priorities and preferences, and this evolution should not be ignored, but rather tracked and anticipated. It is therefore crucial to recognize that these preferences are not static, but rather dynamic, evolving over time in response to factors such as market trends and technological advances. To the best of our knowledge, this study is the first to address the problem of GSS based on changing customer requirements in a fuzzy environment by introducing an integrated model that combines the use of Markov chain analysis with an improved Fuzzy BWM method and the Fuzzy TOPSIS approach.

The Markov chain is a mathematical model that describes a stochastic process in which a system moves from one state to another according to certain transition probabilities. In the context of changing customer preferences, this can be interpreted as the transition from one preference state to another over time [19]. Each state of the Markov chain could represent a specific set of customer preferences at a given time, and the transitions between these states would reflect changes in customer preferences over time. Markov chains have recently been successfully applied to capture the changing behavior of consumers and users [4,9,19,22,23]. [5] is a pioneer in the consideration of customer preferences in supplier selection problems, being the first to integrate Markov chain with MCDM methods in this area. However, his model could be improved by taking into account the uncertainty associated with this decision-making process, also by considering environmental factors.

Based on the preceding discussion, it is evident that numerous MCDM based approaches have been introduced in the literature to aid managers in supplier selection. However, these approaches often lack one or more of the following essential characteristics: the ability to take account of changing priorities in customer requirements when selecting suppliers, integration of customers' requirements into the weighting of selection criteria, consideration of both economic and environmental factors, addressing uncertainty and fuzziness in the decision-making process, and ensuring precise consistency in pairwise comparisons. This paper presents an integrated model for GSS and evaluation, exploiting Markov chain to track and predict the evolution of customer preferences. This approach is complemented by an enhanced and simplified Fuzzy BWM method, surpassing conventional Fuzzy BWM for criteria weighting. Additionally, the

Fuzzy TOPSIS method is employed to effectively rank and prioritize suppliers based on their performance.

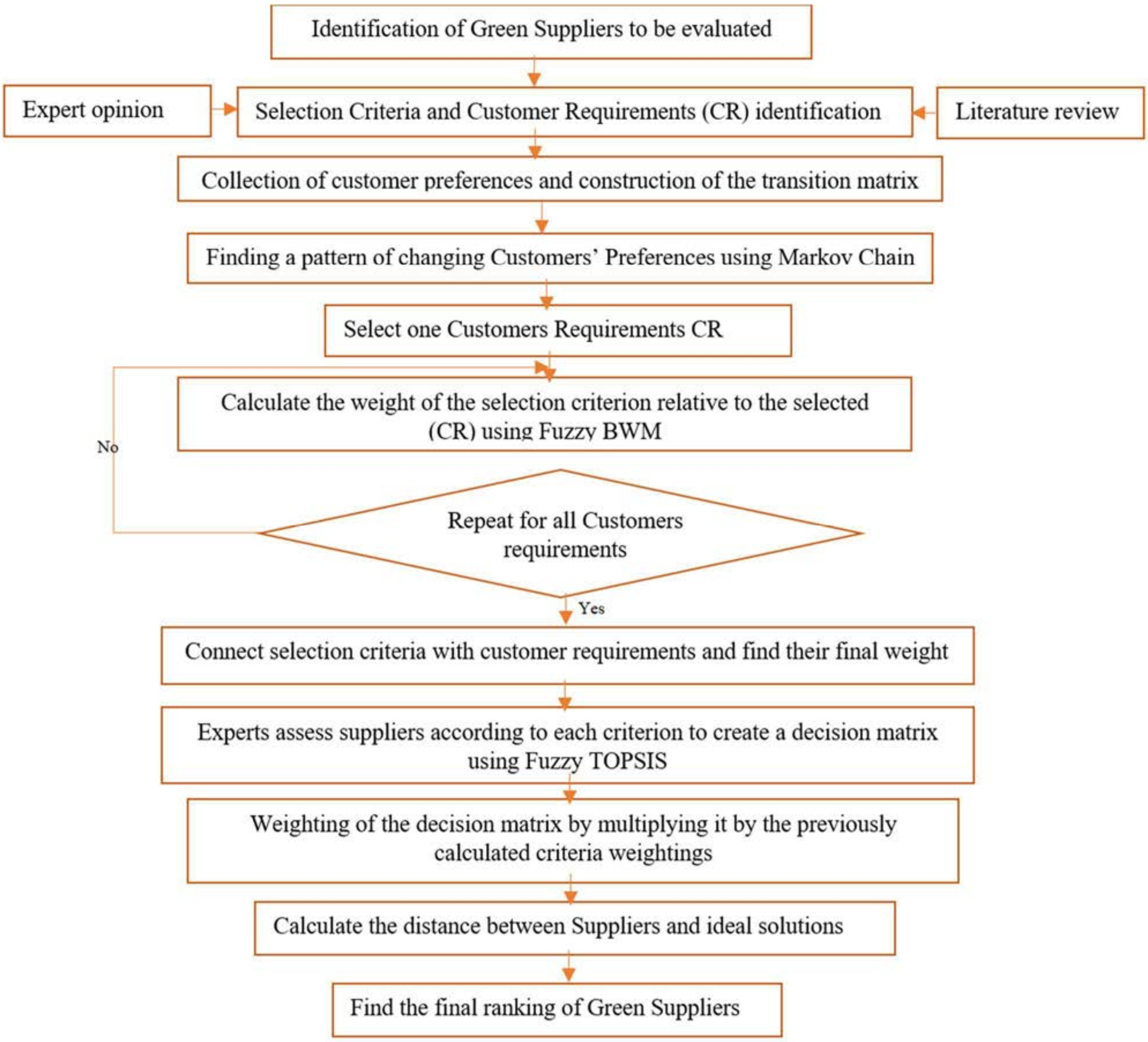

Figure 1 Flowchart of the proposed approach

3 Methods

In this paper we propose an integrated framework for GSS. This approach uses Markov Chain combined with Fuzzy MCDM methods to evaluate the ecological performance of suppliers based on changing customer preferences. Markov chain is applied to track and predict customer preferences. This Markov-generated model is then integrated with the Fuzzy BWM method to find weights for the selection criteria while taking into account customer requirements. These weights are then used to rank the alternatives using the Fuzzy TOPSIS method.

The main steps of the proposed approach proposed are illustrated in the flowchart in Figure1.

3.1 Data collection

This step aims to identify the list of potential suppliers to be evaluated, relevant selection criteria to be considered, and the customers' initial preferences. It is important to note that these preferences are not always stable and may evolve over time. Therefore, through a questionnaire survey among customers, we collect their initial preferences and need to monitor the evolution of these preferences over time, as customers reassess their priorities. To develop the questionnaire, we first carried out a literature review to identify the relevant customer requirements to be assessed. Next, we formulated the questions in collaboration with experts in the field to ensure their relevance and validity. The questionnaire was pre-tested on a pilot sample to refine the list of requirements and ensure clarity. The questionnaire was validated by a panel of experts comprising researchers and practitioners in the field of supply chain management.

In order to collect their initial preferences, the company's customers are asked to rate Customer Requirements (CR) on a 5-point Likert scale. These questionnaires are then regularly redistributed to monitor changes in customer preferences. The questionnaire is distributed once the purchase has been made, enabling customers to fully grasp their needs at that point. The questionnaire was distributed electronically via sales department e-mails to a targeted sample of the company's customers.

3.2 Markov Chain

The Markov chain is a mathematical model that describes a stochastic process in which a system moves from one state to another according to certain transition probabilities. In the context of changing customer preferences, this can be interpreted as the transition from one preference state to another over time. Each state of the Markov chain could represent a specific set of customer preferences at a given time, and the transitions between these states would reflect changes in customer preferences over time.

Transition matrix construction process: The transition matrix is constructed by estimating the probability of a user transitioning from one requirement to another over time. This is done by observing customer's priorities over time and identifying the proportion of customers who regard a particular requirement as their most important and wish to switch to another requirement. The probability of this transition is then calculated using (1) that consider the number c_{ik} of customers who initially placed a requirement *(i)* at the top of their priority list and b_{ijk} the number of customers who wish to change their priority to another requirement *(j)* during the period k. Once the probabilities are estimated, they are used to construct the transition matrix. It is a square matrix that represents the probabilities of transitioning from one requirement to another and is used in the Markov chain analysis to track changes in customer's requirements over time.

$$\gamma_{ijk} = \frac{b_{ijk}}{c_{ik}} \quad (1)$$

Finding the final Pattern process: The final pattern of customer's requirements priorities ($FPCR$) can be derived by initially equating the values of this list $FPCR$ to those of the initial list of Customers' requirements $IPCR$. Subsequently, the iterative process involves the multiplication of the transpose of the vector ($FPCR$) by the transition matrix (TM), as illustrated in the following equation (2):

$$FPCR^{(k)T} = FPCR^{(k-1)T} \times TM \quad (2)$$

where $k = 1, 2, 3, \ldots, max$ is the number of multiplications. Due to the inherent convergence of stochastic matrices, it is anticipated that the matrices will converge to the same values after three to five multiplications. As stated in [4], [19], the adjusted priorities generated by the Markov chain represent a more robust model of future customer preferences, and are independent of initial customer preferences, suggesting the importance of concentrating efforts on the development of a transition matrix rather than on recording consumers' initial preferences.

3.3 Connecting Customers' Requirements and Selection Criteria using Fuzzy BWM

In order to obtain the optimal weight of selection criteria with respect to the selected (CR), the Fuzzy BWM is applied. The main steps of the improved simplified fuzzy BWM according to [24] are described as follows:

Step 1: From the set of criteria to be evaluated, the decision-maker is tasked with discerning the most favorable and unfavorable criteria from the set of selection criteria. The variables n_B^k and n_W^k respectively represent the counts of criteria identified as the best and worst ones in the decision-making process.

Step 2: The decision-maker express his preferences using linguistic terms to carry out comparisons of the "best" criteria against the remaining criteria. These preferences are then translated into triangular fuzzy numbers (TFN) and represented in the AB vector (3).

$$AB = (\tilde{a}_{B1}, \tilde{a}_{B2}, \ldots, \tilde{a}_{Bn}) \quad (3)$$

Where $\tilde{a}_{Bi}$ represents the preference of the best criterion against the ith criterion and logically $a_{BB} = 1$.

Step 3: similarly, the DM carries out a comparison in linguistic terms of all criteria over the worst criteria. After converting these preferences into (TFNs), they are listed in the AW vector (4):

$$AW = (\tilde{a}_{1W}, \tilde{a}_{2W}, \ldots, \tilde{a}_{nW}) \quad (4)$$

Where $\tilde{a}_{iW}$ represents the preference of the ith criterion against the worst criteria and logically $a_{WW} = 1$.

Step 4 : Calculation of criteria weight relative to *best-to-others vector AB* and are denoted as (5), (6), (7):
$\tilde{w}_i^{AB} = (l_i^{AB}, m_i^{AB}, u_i^{AB})$

From $$\tilde{w}_B^{AB} / \tilde{w}_i^{AB} = n_B \tilde{a}_{Bi} \quad (5)$$

and $$\sum_i^n \tilde{w}_i = 1 \quad (6)$$

we obtain: $$\tilde{w}_B^{AB} = \frac{1}{\sum \frac{1}{n_B * \tilde{a}_{Bi}}} \quad (7)$$

Replacing the value of $\widetilde{w}_B^{AB}$ in equation (3) we obtain the criteria weights relative to *best-to-others vector AB* (8):

$$\widetilde{w}_i^{AB} = \frac{\widetilde{w}_B^{AB}}{n_B * \tilde{a}_{Bi}} \tag{8}$$

Step 5 : Calculation of criteria weight relative to *others-to-worst vector AW*. and are denoted as: $\widetilde{w}_i^{AW} = (l_i^{AW}, m_i^{AW}, u_i^{AW})$. Similarly, using equation (9) we calculate the relative weight of the worst criterion, then replace its value in equation (10) to obtain criteria weight relative to *others-to-worst vector*.

$$\widetilde{w}_W^{AW} = \frac{1}{\sum n_W * \tilde{a}_{iW}} \tag{9}$$

$$\widetilde{w}_i^{AW} = \widetilde{w}_W^{AW} * n_W * \tilde{a}_{iW} \tag{10}$$

Step 6: The final weighting of each criterion with respect to the selected (CR) is determined by averaging the previously calculated relative weights using the following equation (11):

$$\widetilde{w}_i^{*} = \frac{\widetilde{w}_i^{AB} + \widetilde{w}_i^{AW}}{2} \tag{11}$$

The selection criteria {C1...Cn} are evaluated with respect to each customer requirement (CR). Whenever a set of weights for the criteria is calculated, these weights form the rows of the *(CR-C)* matrix. Now, the goal is to find the W_{CR} matrix (12) containing the final weights of the selection criteria considering their relationships with the customer requirements (CR). This matrix is determined by the product of the previously calculated weights matrix *(CR-C)* using the Fuzzy BWM method with the final pattern of customer's requirements priorities ($FPCR$) obtained by applying the Markov chain.

$$W_{CR} = (CR\text{-}C) * (FPCR) \tag{12}$$

3.4 *Fuzzy TOPSIS approach for alternative prioritization*

The main steps of the Fuzzy TOPSIS approach according to [25] are described as follows:

Step1: Construction of the fuzzy decision matrix D with *m* alternatives and *n* criteria by converting linguistic preferences into (13)

$$\text{TFNs: } D = \left[\widetilde{x_{ij}}\right]_{mxn} \tag{13}$$

where $\widetilde{x_{ij}} = (a_{ij}, b_{ij}, c_{ij})$.

Step2: Construction of the normalized fuzzy decision matrix after identifying the cost and benefit criteria from the set of selection criteria. The matrix is presented as:

$\tilde{R} = \left[\widetilde{r_{ij}}\right]_{mxn}$, i=1,…,m ; j=1,2,…,n where (14), (15):

$$\widetilde{r_{ij}} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \text{ and } c_j^* = \max_i c_{ij} \text{ (benefit criteria)} \tag{14}$$

$$\widetilde{r_{ij}} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \text{ and } a_j^- = \min_i a_{ij} \text{ (cost criteria)} \tag{15}$$

Step3: Construction of the weighted normalized fuzzy decision matrix by multiplying the previous matrix by the weights of each criterion calculated previously using the Fuzzy BWM method.

Step4: determine the Fuzzy positive ideal FPIS (A+) and Fuzzy negative ideal FNIS (A-) (16), (17):

$$A^+ = (v_1^+, v_2^+ \dots, v_n^+) \tag{16}$$

$$A^- = (v_1^-, v_2^- \dots, v_n^-) \tag{17}$$

Where (18), (19):

$$v_j^+ = \max(\widetilde{v_{ij}}) \tag{18}$$

and

$$v_j^- = \min(\widetilde{v_{ij}}) \tag{19}$$

Step 5: Calculate the distance of each weighted alternative from both (FPIS) and (FNIS) using the following equations (20), (21):

$$d_i^+ = \left\{\sum_{j=1}^n \left(v_{ij} - v_{ij}^+\right)^2\right\}^{\frac{1}{2}} \quad , i = 1 \dots m \tag{20}$$

$$d_i^- = \left\{\sum_{j=1}^n \left(v_{ij} - v_{ij}^-\right)^2\right\}^{\frac{1}{2}} \quad , i = 1 \dots m \tag{21}$$

Step 6: Calculate the closeness coefficient, used to rank the alternatives using the following formula (22):

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{22}$$

4 Case study

To assess the applicability and effectiveness of our proposed approach, we conducted a real-world case study within a Moroccan company specializing in the manufacturing of construction materials. This industry-leading company is committed to reducing its ecological footprint while providing high-quality products. It has already implemented Green initiatives such as the use of recycled materials, carbon emission reduction, and process optimization to minimize waste. This company has a keen interest in our study and is convinced that the findings could provide valuable recommendations to further enhance its commitment to sustainability and satisfying its customers' requirements.

Table 1 A brief description of selection criteria

Selection criteria	**Description**
Cost (C1)	Product cost, freight cost and cost reduction capability
Quality (C2)	Refers to the level of excellence of the product
Delivery (C3)	The ability to meet specified delivery schedules: order fill rate, the availability of the product, lead time, order frequency
Air emission (C4)	Measures to reduce greenhouse gas emissions, air pollutants, and other harmful airborne substances.
Waste water (C5)	The efficiency of wastewater treatment systems and compliance with environmental regulations regarding water pollution
Use of harmful materials (C6)	It assesses efforts to minimize or eliminate the use of harmful and toxic substances and replace them with eco-friendly alternatives.
Green packaging (C7)	Use of sustainable packaging materials and practices.
Recycle (C8)	The implementation of recycling programs, the percentage of materials recycled, and the use of recycled materials
EMS and ISO 14001 certification (C9)	The presence of an environmental management system (EMS), a regulatory compliance and environmental certification such as ISO14000

Selection criteria:

The identification of Supplier selection criteria requires meticulous attention, taking into account the characteristics of the industrial sector under study and responding to the specific requirements of decision-makers. Studies have shown that, when selecting green suppliers, the integration of sustainable practices should not be at the expense of traditional criteria. Both aspects need to be taken into account in the decision-making process. The criteria adopted in this study are based on previous research conducted by author [24], which identified nine selection criteria. Economic criteria include: Cost (C1), quality (C2), delivery (C3), and Ecologic criteria include: Air emission (C4), Waste water (C5), Use of harmful materials (C6), Green packaging (C7), Recycle (C8), Environmental Management Information System and ISO 14001 certification (C9). A brief description of each criterion is given in Table 1.

Table 2 A brief description of customer requirements

Customer Requirements	**Description**
Product Quality (CR1)	This includes durability, resilience, and compliance with industry standards and commonly adopted specifications.
Price (CR2)	Market-competitive prices, ability to offer payment facilities and discounts.
Compliance with environmental standards (CR3)	Materials that comply with environmental standards, minimize ecological impact and are manufactured in a sustainable manner.
Technical support and after-sales service (CR4)	Ability to provide technical advice and solutions to potential problems, installation assistance, warranty, easy replacement in the event of failure.
Stock availability (CR5)	Ability to supply requested quantities within reasonable lead times.

5 Results

The following section presents the results of applying the proposed approach, highlighting the data collected and the analyses carried out. These results are then compared with those obtained using different methods, to assess their relative effectiveness and relevance.

5.1 Results from the application of the proposed approach

Data collection:

The data collection process in this approach initiates with identifying customer preferences. Recognizing that these preferences may evolve over time, a questionnaire survey is implemented. Questionnaires are periodically redistributed to the organization's customers to capture the evolution of their preferences. By leveraging the questionnaire results, the transition matrix (*TM*) is constructed following the steps outlined in Section 3.2. The fallowing Set of Customer Requirements (CR) is adopted in this paper: (Product Quality (CR1), Price (CR2), Compliance with environmental standards (CR3), Technical support and after-sales service (CR4), Stock availability (CR5)). Table 2 provides a brief description of each (CR).

The initial list of (CR) Priorities (IPCR) and the transition Matrix (TM) are obtained as follows:

$$IPCR = \begin{matrix} \textbf{Quality } CR1 & 0.39 \\ \textbf{Price } CR2 & 0.14 \\ \textbf{Env.stand } CR3 & 0.16 \\ \textbf{Tech.supp } CR4 & 0.12 \\ \textbf{Stock avail } CR5 & 0.19 \end{matrix} \quad and \quad TM = \begin{matrix} & CR1 & CR2 & CR3 & CR4 & CR5 \\ CR1 & 0.35 & 0.22 & 0.09 & 0.11 & 0.23 \\ CR2 & 0.29 & 0.28 & 0.27 & 0.08 & 0.08 \\ CR3 & 0.16 & 0.10 & 0.31 & 0.15 & 0.28 \\ CR4 & 0.25 & 0.13 & 0.12 & 0.33 & 0.17 \\ CR5 & 0.28 & 0.30 & 0.10 & 0.10 & 0.29 \end{matrix}$$

Finding a pattern of changing Customers' Preferences using Markov Chain:

To predict future customer preferences based on initial preferences and the transition matrix, we applied the Markov Chain, as outlined in Section 3.2.

$$FPCR^{(1)\,T} = FPCR^{(0)\,T} \times TM = (0.286\ 0.20\ 0.156\ 0.137\ 0.221) \quad (19)$$
$$FPCR^{(2)\,T} = FPCR^{(1)\,T} \times TM = (0.283\ 0.199\ 0.164\ 0.139\ 0.215) \quad (20)$$
$$FPCR^{(3)\,T} = FPCR^{(2)\,T} \times TM = (0.282\ 0.197\ 0.168\ 0.141\ 0.212) \quad (21)$$
$$FPCR^{(4)\,T} = FPCR^{(3)\,T} \times TM = (0.277\ 0.201\ 0.170\ 0.139\ 0.213) \quad (22)$$
$$FPCR^{(5)\,T} = FPCR^{(4)\,T} \times TM = (0.277\ 0.201\ 0.170\ 0.139\ 0.213) \quad (23)$$

As demonstrated by (19), (20), (21), (22) and (23), the matrix stabilized after five multiplications, consistently yielding the same values thereafter. This stabilization illustrates the convergence of the model. The final pattern of customers' preferences is as follows:

$$FPCR = \begin{matrix} CR1 & CR2 & CR3 & CR4 & CR5 \\ 0.277 & 0.201 & 0.170 & 0.139 & 0.213 \end{matrix}$$

Connecting Customers' Requirements and Selection Criteria using Fuzzy BWM:

The final pattern of customers' priorities is obtained using the Markov Chain. This final list of priorities is then used as an input to the Fuzzy BWM method in order to connect the Customers' requirements to the selection criteria. For each chosen Customer Requirement, the Best and Worst criteria are identified, and pairwise comparisons are conducted. The weights of the selection criteria are then computed following the procedures outlined in Section 3.

Table 3 Selection criteria comparisons with respect to "CR1=ProductQuality"

		C1	C2	C3	C4	C5	C6	C7	C8	C9
Quality	C_B: C2	(2,3,4)	(1,1,1)	(5,6,7)	(5,6,7)	(5,6,7)	(3,4,5)	(4,5,6)	(3,4,5)	(2,3,4)
	C_W: C3	(6,7,8)	(7,8,9)	(1,1,1)	(2,3,4)	(2,3,4)	(3,4,5)	(4,5,6)	(5,6,7)	(6,7,8)
Optimal weights		(0.094, 0.140, 0.214)	(0.211, 0.267, 0.329)	(0.030, 0.041, 0.054)	(0.040, 0.064, 0.097)	(0.040, 0.064, 0.097)	(0.058, 0.090, 0.138)	(0.063, 0.093, 0.136)	(0.068, 0.102, 0.153)	(0.094, 0.140, 0.214)

Table 3 shows the values of the pairwise comparisons and the optimal weights for the selection criteria associated with the customer requirement CR1. In a similar way, pairwise comparisons are carried out for the other remaining customer requirements: (CR2, CR3, CR4 and CR5) and the criteria weights are retained for each iteration.

The resultant weights are systematically organized and presented in the following Fuzzy matrix (*CR-C)*:

CR-C) =

	C1	C2	C3	C4	C5	C6	C7	C8	C9
(CR1)	(0.094, 0.140, 0.214)	(0.211, 0.267, 0.329)	(0.030, 0.041, 0.054)	(0.040, 0.064, 0.097)	(0.040, 0.064, 0.097)	(0.058, 0.090, 0.138)	(0.063, 0.093, 0.136)	(0.068, 0.102, 0.153)	(0.094, 0.140, 0.214)
(CR2)	(0.245, 0.299, 0.355)	(0.095, 0.136, 0.192)	(0.095, 0.136, 0.192)	(0.029, 0.037, 0.047)	(0.03, 0.037, 0.047)	(0.059, 0.089, 0.129)	(0.055, 0.082, 0.118)	(0.045, 0.07, 0.133)	(0.08, 0.113, 0.159)
(CR3)	(0.022, 0.028, 0.035)	(0.057, 0.082, 0.117)	(0.033, 0.052, 0.078)	(0.061, 0.089, 0.129)	(0.061, 0.089, 0.129)	(0.183, 0.225, 0.270)	(0.076, 0.111, 0.168)	(0.067, 0.100, 0.155)	(0.183, 0.225, 0.270)
(CR4)	(0.093. 0.134. 0.198)	(0.113. 0.165. 0.252)	(0.249. 0.309. 0.379)	(0.030. 0.039. 0.049)	(0.030. 0.039. 0.049)	(0.051. 0.082. 0.126)	(0.047. 0.075. 0.115)	(0.047. 0.075. 0.115)	(0.051. 0.082. 0.126)
(CR5)	(0.107. 0.157. 0.239)	(0.107. 0.157. 0.239)	(0.234. 0.295. 0.362)	(0.029. 0.037. 0.047)	(0.029. 0.037. 0.047)	(0.060. 0.091. 0.136)	(0.045. 0.072. 0.109)	(0.031. 0.054. 0.085)	(0.065. 0.101. 0.154)

The final fuzzy weighting (Table 4) of the selection criteria taking into account customer requirements is then obtained according to equation (9).

Table 4 final weights of selection criteria considering CR

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
final aggregated weights	(0.115, 0.156, 0.215)	(0.126, 0.172, 0.236)	(0.118, 0.153, 0.197)	(0.038, 0.054, 0.075)	(0.038, 0.054, 0.075)	(0.079, 0.112, 0.157)	(0.058, 0.087, 0.129)	(0.052, 0.081, 0.129)	(0.094, 0.132, 0.188)

Green Supplier Assessment using Fuzzy TOPSIS:
In this section, we utilize the Fuzzy TOPSIS method for evaluating green suppliers and determining their final ranking. Each expert contributes individual linguistic assessments, translated into triangular fuzzy numbers. These assessments are aggregated into a consensus Fuzzy decision matrix, normalized with consideration to the previously obtained criteria weights through the Fuzzy BWM method. The weighted normalized fuzzy decision matrix is then calculated based on the multiplication of the normalized matrix and the criteria weights previously calculated, the results are shown in Table 5. Finally, the closeness coefficient is computed, relying on both FPIS and FNIS, resulting in the final ranking of green suppliers showed in Table 6.

Table 5 The Weighted and Normalized fuzzy decision matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9
GS1	(0.018, 0.036, 0.092)	(0.054, 0.123, 0.236)	(0.056, 0.113, 0.197)	(0.006, 0.012, 0.028)	(0.004,0.007, 0.011)	(0.023, 0.051, 0.157)	(0.032, 0.068, 0.129)	(0.021, 0.049, 0.104)	(0.066, 0.123, 0.188)
GS2	(0.038,0.156, 0.215)	(0.024, 0.041, 0.067)	(0.051, 0.087, 0.137)	(0.004, 0.007, 0.013)	(0.006, 0.01, 0.017)	(0.016, 0.029, 0.049)	(0.009, 0.016, 0.029)	(0.008, 0.016, 0.041)	(0.010, 0.015, 0.035)
GS3	(0.013, 0.02, 0.038)	(0.018, 0.074, 0.168)	(0.015,0.033, 0.094)	(0.009,0.023, 0.075)	(0.01,0.032, 0.075)	(0.021,0.043, 0.112)	(0.036, 0.074, 0.129)	(0.027,0.062, 0.129)	(0.073,0.132, 0.188)

Table 6 The final ranking of the three Green Suppliers

	d+	d-	CC	Ranking
GS1	0,196	0,514	0,724	1
GS2	0,528	0,182	0,256	3
GS3	0,287	0,420	0,594	2

5.2 Comparison with other methods

To assess the effectiveness of the proposed model and validate the obtained results, a comparative study is conducted.

Comparing criteria weightings: This study involves calculating the weights of selection criteria in two different ways: using the methodology proposed in this paper and using the Fuzzy BWM method without considering customer requirements. The aim of this comparative study is to evaluate the impact of customer requirements on the criteria weighting process in the context of GSS. The comparison results are presented in Figure 2.

Comparing green suppliers ranking: Beyond the methodology proposed in this paper, three other existing GSS models from literature are considered for comparison. Specifically, the Fuzzy TOPSIS method. [24] proposes a novel model combining the use of an improved and simplified Fuzzy BWM and Fuzzy TOPSIS. Authors have demonstrated the superiority of the proposed model over other existing methods in terms of consistency and relevance of the results obtained. Additionally, the combination of the well-known Fuzzy AHP and Fuzzy TOPSIS methods is chosen as another comparative approach. The comparison results are presented in Figure 3.

6 Discussion and implication

In this paper, we propose a hybrid approach combining Markov Chain, fuzzy theory and MCDM techniques to address GSS. This approach takes into account customer requirements, and pays particular attention to the fact that customer priorities are constantly changing over time. The application of Markov chain enabled us to track this change and predict a pattern of customer preferences.

After applying the Markov chain to initial customer preferences, the resulting pattern shows an adjustment in customer preference priorities over time. Initially, **quality** was the dominant priority with a weighting of 0.39, but according to the Markov model, this weighting decreased to 0.277. In contrast, **stock availability**, initially at 0.19, increased to 0.213, indicating a shift in priority towards this criterion. These results suggest a shift in customer preferences towards a greater focus on stock availability, while quality has become relatively less dominant. As for the "**Technical support and after-sales service**" criterion, initially it had a weighting of 0.12, but according to the Markov model, this weighting increased slightly to 0.139. This could indicate a growing recognition of the importance of technical support and after-sales service for customers over time. Indeed, in this industrial sector, the purchase of building materials is often a major investment for customers, and they are keen to ensure that their money is well spent. Customers often need technical support for the installation and use of materials, particularly for complex or specialized products. An effective after-sales service can ensure that customers receive the assistance they need to resolve potential problems and maximize the value of their purchases [26]. This interpretation highlights the importance of monitoring trends in customer preferences to proactively adjust supplier selection strategies.

After obtaining the new pattern of customers' future preferences, a connection between these preferences and the selection criteria is established by applying the Fuzzy BWM method to obtain the final weights of the selection criteria. These results indicate that **Quality** (0.175) is the most important criterion, followed by **Cost** (0.159), **Delivery** (0.155) and **EMS** (0.140), suggesting that customers attach great importance to the quality of building materials. We conducted a comparative study with the aim of obtaining the weights of the selection criteria in two different ways: using the methodology proposed in this paper, and using a criteria weighting method existing in the literature without considering customer requirements. The results of this comparative study reveal a difference in the weights of the selection criteria between the two approaches. When customer requirements are taken into account, the weights assigned to certain criteria, such as **Cost**, **Delivery** and **Use of Harmful Materials,** increase considerably compared to the method that does not take these requirements into account. This suggests that customers attach greater importance to these aspects. On the other hand, criteria such as **quality** and **EMS** see their weights decrease slightly when assessed against customer requirements. This may indicate that customers attach great importance to these criteria, and are willing to pay a higher price for quality and environmentally-friendly products. These results underline the importance of understanding and responding to changing customer needs and preferences in the supplier selection process.

These criteria have practical implications for environmental policy makers and for companies seeking to improve their sustainable supply chain. Our recommendations include adopting strategies to strengthen performance on each of these criteria in order to optimize overall sustainability results.

The Markov chain has been successfully used in previous studies to predict the evolution of customer needs [4,9,19,23]. However, after reviewing the existing literature, few articles combine the use of the Markov chain with MCDM techniques when selecting suppliers. The only existing supplier selection model in the literature that integrates Markov chain with MCDM techniques does not take into account the uncertainty associated with this selection process [5]. Our approach, which takes advantage of fuzzy set theory, offers an effective response to this uncertainty, thus establishing a robust framework for managing ambiguous or imprecise information. Moreover, the model proposed by [5] evaluates suppliers solely on the basis of economic criteria. Our study demonstrated the importance attached by customers to environmentally-friendly products, underlining the need to integrate ecological criteria into the supplier selection process.

After obtaining the weights of the selection criteria, these weights are then integrated into the Fuzzy TOPSIS method to rank the suppliers. The ranking results in the following order: GS1, followed by GS3, then GS2. In order to validate the results obtained, we carried out a comparative study in which we ranked the 3 suppliers using four different methods. Figure 3 shows the ranking results based on the proposed framework and the three methods involving the same data used in the case study. According to Figure 3, the results of the four methods are quite similar. All methods ranked **GS1** as the best green supplier. And **GS3** is ranked second in all methods, with the exception of the Fuzzy TOPSIS method, where it is ranked last. Thus, it can be concluded that the results obtained are consistent and can be considered valid and robust, reinforcing the reliability of the proposed approach and its applicability in the decision-making process.

Figure 2 Comparison of selection criteria weightings

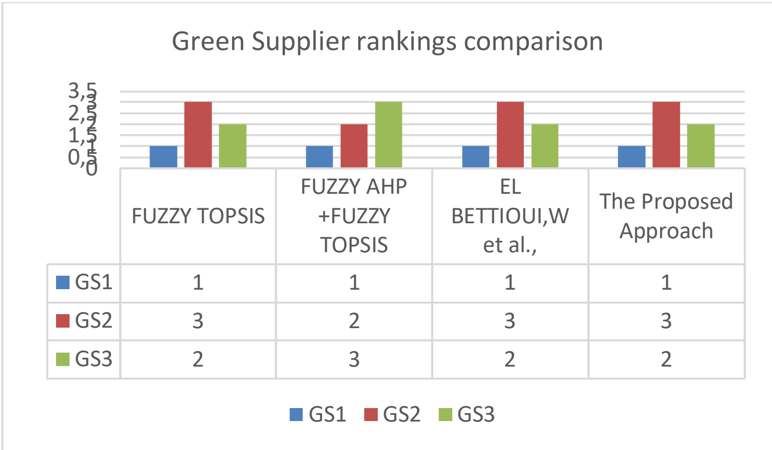

Figure 3 Green Supplier rankings comparison

7 Conclusion

GSS presents crucial challenges in today's sustainability-driven environment. Taking customer requirements into account in this process has become essential, as it helps to ensure that the chosen suppliers meet customers' specific expectations for environmentally-friendly products. However, customer preferences are not static; they evolve over time. This dynamic requires an anticipatory approach to predicting future customer preferences. Understanding how customers can change their minds and adapt their preferences becomes a key element in more accurate supplier selection, aligned with market trends and consumer expectations.

In this paper we propose an integrated framework for GSS. This approach uses Markov Chain combined with Fuzzy MCDM methods to evaluate the ecological performance of suppliers based on changing customer preferences. Markov chain is applied to track and predict customer preferences. This Markov-generated model is then integrated with the Fuzzy BWM method to find weights for the selection criteria while taking into account customer requirements. These weights are then used to rank the alternatives using the Fuzzy TOPSIS method.

To test the effectiveness of the proposed model, we conducted a real-life case study involving the evaluation of three green suppliers, taking into account five customer requirements and nine selection criteria. To validate the results obtained, we conducted a comparative study involving the calculation of selection criteria weights in two different ways: one in which customer requirements were integrated into the supplier evaluation process, and one in which these requirements were not taken into account. In addition, we compared the ranking of green suppliers using three different supplier selection models existing in the literature. The results obtained in this work demonstrate that the proposed hybrid framework is very consistent, overcomes the uncertainty associated with this decision-making and is capable of proactively satisfying customer requirements.

This research aims to enrich the current literature in the area of GSS. Despite its advantages, our method also presents some critical limitations that need to be considered. Firstly, a sensitivity analysis of the proposed model is required to test different scenarios reflecting various situations that decision-makers may face when evaluating suppliers. This could involve modifying the list of customer requirements or the list of alternatives to ensure the consistency of the results obtained. The second limitation concerns the non-generalizability of the proposed model, as it is based on a specific case study and may not be applicable to all GSS problems. In view of the limitations raised, we propose to add a new perspective to the scientific literature by considering different possible scenarios and extending the study to different industries and economic contexts.

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Role of marketing information systems in improving the performance of logistics companies with special reference to Nagpur

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Keywords: flow, information, logistics, MIS, performance.
Abstract: In the current market environment, organizations must endeavour to speed up their decision-making. Different investigations show that this impacts both competitive situations just as monetary after-effects of those organizations, in the long and short term. Marketing Information systems (MIS) serve as an essential tool for driving the company's performance. Hence, this article aims to assist decision-makers in enhancing the logistics company's performance by ensuring the proper flow of operations. This research is undertaken first to know and understand the role played by MIS on companies' performance and secondly to study the effect of selected factors of MIS on the performance of the companies. The attention will be towards the factors of MIS like Records keeping, Marketing Intelligence systems, Marketing Decision Support Systems, and Marketing Research. This research is carried out in an emerging area called Nagpur (India). 58 was the sample size. The primary data was collected using a questionnaire. Data were collected in March 2024. It was later analyzed using the Ordinary Least Square (OLS) method. Cronbach's Alpha test was done to decide the consistency of the questionnaire variables, and it was found to be 0.892. Since the value exceeded 0.6 the decision was made to rely on the questionnaire. The researchers found that MIS is crucial in making decisions as it helps improve the company's performance. All the selected 4 factors of MIS contribute more or less equally to increasing the performance of the logistics companies. Hence, logistics companies can rely on MIS to improve the company's performance.

1 Introduction

The digitization of promoting resources in fast-growing businesses can significantly enhance growth and efficiency [1]. This effect is especially notable with the integration of advanced technologies, especially the advent of Artificial Intelligence [2]. This advanced technology enhances production and efficiency by improving the packaging process, transportation, fleet management, shipment process, warehousing, inventory management, supply chain management (SCM), and other logistics components. Digitization brings information and this helps for improved decision-making, particularly in this fast-changing customer preference, consequently, the decision-makers need to do a great deal to obtain, measure, and send precisely timely marketing information to make good decisions that can increase their competitive advantage, accordingly adding to their performance [3]. Therefore, looking for information about your current circumstances and rivals is indispensable for business endurance. In addition to Information, Marketing activities such as advertising, personnel selling, packaging, promoting, etc. are used to persuade the wants of the customer and to achieve the organizational objectives. The necessity for Marketing Information Systems (MIS) emerges from the understanding that no single variable can guarantee success. Today, MIS has become an essential component of the marketing decision-making process providing vital insights and guiding strategic choices [4]. It plays a base role in making decisions by the managers as it provides market intelligence to the company. It helps marketing planning by making accessible the right data on the inner organization's real factors and external environment. The necessity for MIS arises from the need to formulate development plans and programs to achieve the pre-defined objectives and goals. Additionally, MIS is needed to monitor and control marketing activities effectively.

MIS upholds decision-making concerning these exercises [5]. MIS is the process adopted by managers for making marketing decisions by collecting data through internal as well as external sources. This data is processed to convert it into useful information. Company managers flow this information to make informed marketing decisions that enhance performance [6]. Many researchers have time and again proved that MIS contributes significantly to enhancing the performance of the company [7]. Marketing Information systems can assume a significant role, for example, in evaluating information needs, creating information and circulation information in an endeavor, and managing the cost of improving the general degree of performance of the organization. MIS helps control everyday exercises and decide on the productive utilization of cash and employees. Thinking about marketing without MIS is impossible and difficult [8]. If an organization lacks MIS, its efficiency in managing logistics, such as flow of information, inventory control, warehousing issues, transportation, etc. is likely to be severely affected, weakening its competitive edge [9]. At long last in the present fast-changing condition, managers need all the better up-to-date information to settle on decisions.

Most organizations today face the challenge of declining levels in logistics, including improper flow of information, inventory control, warehousing, material handling, packaging, etc. That is, there is a swing in the performance of the logistics companies especially after covid 19. Increasing performance benefits the company in several ways, but the real challenge arises when there is a decline in performance. A drop in performance affects the company directly as it is connected with the profit and survival of the company. There can be numerous factors contributing to the decline in performance like information flow, lack of storage/warehousing especially in the case of small-scale industries, transportation, material handling, etc. One of the reasons is the insufficiency of Marketing Information systems. This is especially true when the whole world is now depending on Information Technology and Artificial Intelligence [2,10]. This has encouraged the researcher to undergo this study to know how MIS can be utilized to improve the performance of the logistic companies and thus contribute to the smooth running of the company. The problem is to examine, how performance can be improved or at least maintained with the MIS. This is the circumstance that drove the researcher to accomplish a study to know the roles that could be played by MIS in stimulating the performance of private logistics businesses in the Nagpur region of Maharashtra (India). This study is done to be of incredible assistance and significance to any logistic companies that would like to set out on MIS. It is accepted that toward the end of this research work, the performance level of the organization and the other related companies in the country will be incredibly improved.

The significance of the investigation is to help any association that might want to leave the MIS, to help them in building up a very established organization through the upgrade of performance. It is additionally critical to different organizations in that toward the end of the investigation, they would steadily make references to this work and take the fundamental measures to get together with proficient and powerful MIS that will improve their degrees of performance.

Over the background of the study, it has been observed that recent decades have seen significant technological advancements in Information technology. These advancements are primarily driven by the computerized application of knowledge to business processes. At the same time, technical advancement is also witnessed especially in logistics companies. Technical advancements such as automation in packaging, material handling, SCM, Fleet management, inbound and outbound logistics, etc. [11]. Companies seek knowledge and information in a variety of ways. Achieving this goal requires a lot of information and data to enable management to make the right decisions to survive and improve performance. Therefore, an efficient information system is indispensable to provide the necessary information to the administration. MIS is considered to be the most important of these systems. Hence, this research work is taken.

2 Literature review

Managers and decision-makers are well aware of the competitive intelligence system on the performance of the firm [12]. Another author [13] expresses that data as information can be utilized as a foundation to tackle obstacles, evaluate possible activities, better operational and technical execution, and moderate dangers in decision-making measures, which, as per [14], empower new occasions to occur just as modifications in the company.

Research according to [15], characteristically, the MIS has four interdependent and interrelated elements these are: Records keeping, Marketing Intelligence Systems, Marketing Decision Support Systems, and Marketing hence these four variables were used to carry out this research.

2. 1 Component of MIS

Managers can quickly make decisions thanks to the marketing information system, which is a constant and ongoing activity that serves as a database. The components of MIS include Internal records, market research, intelligence systems, and marketing decision support systems [16].

2.1.1 Internal Record Keeping

Compared to other sources of information, Internal Records (IR) are very easily and quickly accessible [17]. Another research [18] states that internal records and reports of the organization provide much more important and useful information for the arranging, execution, and control process. Similarly, [19] concluded that information about sales for different regions, customers, and products is vital to the sales and marketing manager, regardless of whether surveying the performance of those zones or products.

2.1.2 Marketing Intelligence System

Marketing Intelligence systems are strategies and information sources utilized by decision-makers to shift information from financial matters and work environments that they can utilize in their decision-making [20]. The other author [21] states that marketing intelligence systems comprise a bunch of methodologies and assets utilized by administrators to acquire day-by-day data on changes in the marketing environment.

2.1.3 Marketing Decision Support Systems

The Marketing decision support system is a coordinated arrangement of PC apparatuses permitting a decision taker to cooperate straightly with the PC to recover helpful information in settling on semi-organized and unregulated decisions [22]. Research by [23] depicts that Marketing decision support systems have arisen because of the development and extension of associations to help marketing managers improve their abilities, which includes a computer that encourages strategies for the marketing supervisor to get to data in decision-making.

2.1.4 Marketing Research

It is the precise and target identification, assortment, examination, spread, and utilization of Information & arrangement of issues & openings in sales and publicizing [24]. According to [25], compelling Marketing Research ponders decidedly the marketing execution on the bank staff members in Gaza. Marketing research is utilized to give information that makes it conceivable to make decisions that are unpredictable and reflect issues that the association faces occasionally, or decisions that need to gather information to support it, for example, presenting another item or items to the market [26].

2.2 MIS and Performance

A researcher [27] opined that the effective utilization of MIS, independent of other factors, significantly enhances both individual and organizational performance. Logistics companies will be able to generate relevant customer insights, provide excellent customer service, and achieve business excellence with the proper coordination and utilization of marketing information, marketing information systems, and marketing intelligence [28].

According to the detailed review of the above literature following the research framework, objectives, and hypotheses were designed.

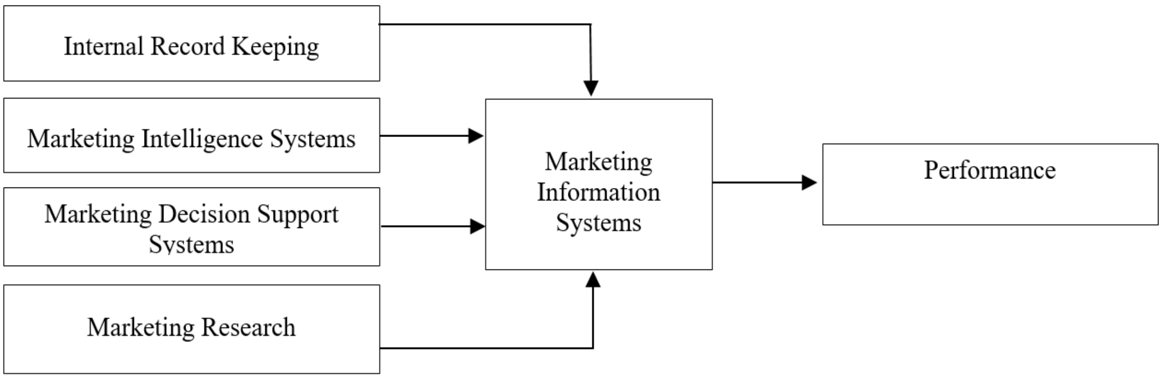

Figure 1 Conceptual framework -MIS on logistics performance

After carefully studying the literature following objectives were framed for the investigation:

- Understand the role played by MIS on the performance of logistics companies.
- To study the effect of Factors, like, Internal Record (IR) Keeping, Marketing Intelligence systems, Marketing Decision Support Systems, and Marketing Research on the performance of selected logistics companies.

According to the objective the hypothesis would be:

H_0: No important relationship exists between the selected factor contributing and the performance of the logistic company.

3 Methodology

The objectives of this study were to understand the role of MIS on the performance of the companies and the effect of selected factors on performance. It is restricted to the logistics field only where it involves a chosen few renowned logistics corporations and does not take into account the whole sector. As a result, these selected enterprises are typical of the logistics industry. Thus, this investigation takes into consideration the staff members of those transport companies, their owners, and people who have direct relations with them. The research work is exploratory and completely survey-based using a structured questionnaire. Sources of secondary data were books, research articles, websites, etc. The questionnaire was distributed to 61 employees, out of which 58 respondents were fully useable for the study hence making the sample size 58 respondents, and the response rate was 95.08%. respondents were randomly selected. The data was collected in March 2024. The research instrument was a survey using a structured question. Quantitative responses were examined utilizing tools for example reliability statistics, regression, and the Ordinary Least Square (OLS) method. SPSS (version 23) was used for the research work. On a 5-point rating scale, closed-ended questions were used. The scale has ranged from strongly agree to 5 to strongly disagree to 1. The area of the research work was Nagpur, Maharashtra (India).

4 Results and discussions

Data collected from the respondents are reflected here. This data is converted into useful information to conclude. The results of Hypothesized relationships among the variables are reported.

Table 1 Case summary

Case Processing Summary			
		N	**%**
Cases	Valid	58	100.0
	Excluded	0	.0
	Total	58	100.0
a. Listwise deletion based on all variables in the procedure.			

Source: Output of SPSS

Table 2 Reliability statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	No. of Items
.892	.893	35
.892	.893	35

Source: Output of SPSS

As shown in Table 1 and Table 2, the reliability of the data is presented in the table. This dependability was checked utilizing Cronbach's alpha. As shown reflected in the table coefficient of 0.892 indicates the good dependability of the questionnaire.

Table 3 Model summary

Model	R	R Square	Adjusted R Square	Std. error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.961a	.939	.905	.23191	.938	93.374	2	35	.000	1.987
a. Predictors: (Constant), Record Keeping, Marketing Intelligence Systems, Marketing Decision Support Systems, and Marketing Research.										

Source: Output of SPSS

The coefficient of determination (R^2), which measures the proportion of the performance variation that is clarified by the set of predictor variables (Record Keeping, Marketing Intelligence Systems, Marketing Decision Support Systems, & Marketing Research), has a value of 93.8 percent (Table 3). In other words, 93.8% of modifications in the performance are caused by independent variables (Record Keeping, Marketing Intelligence Systems, Marketing Decision Support Systems, and Marketing Research). Whereas, 6.2% of changes are caused by other factors. The adjusted R^2 value is 0.905 and is derived from the R^2 adjusted for the model's number of predictors. The Durbin–Watson test statistic is used to determine whether a regression investigation's prediction errors contain autocorrelation. Since the Durbin–Watson statistic is less than 2, as shown in the preceding table, there is abundant evidence of a positive sequential correlation between the indicators.

Table 4 Anova model

Model	Sum of Squares	Df	Mean squares	f	Sig.
Regression	28.195	6	5.034	92.171	.000a
Residual	2.538	50	0.063		
Total	30.733	56			

Source: Output of SPSS

The table above (Table 4) depicts the results obtained in the analysis of regression of the dependent variable (Performance) and the other four independent variables. The determined F-value shows that when the outcome was contrasted with F-calculated, it was critical: F(5/50)=92.171, p<0.005, which straightforwardly infers that the chosen autonomous factors were huge variables that influence the efficiency of the dependent variable.

Table 5 Regression model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	.409	.153		2.780	.010
Internal Record Keeping	.127	.056	.142	2.147	.036
Marketing Intelligence System	.128	.052	.181	2.282	.028
Marketing Decision Support System	.125	.055	.172	2.193	.034
Marketing Research	.131	.049	.152	2.171	.029

Source: Output of SPSS

The Regression result for the Marketing Information Systems as a contributing factor to performance is shown in the table above (Table 5). This table confirms the factors (Record Keeping, Marketing Intelligence Systems, Marketing Decision Support Systems, and Marketing Research) being significant, t(2.780) = 2.147, 2.282, 2.193, and 2.171 respectively, p<0.05. It can be concluded that the factors are of comparable significance and directly contribute to increasing the logistics company's performance.

The alternative hypothesis was accepted, and the main hypothesis was rejected. This directly implies that the selected independent factors are contributing to the performance of the logistics company. These factors have a significant part to play in the performance of the company.

For companies, a key performance indicator of their own is customer satisfaction has always been the top priority required to attain excellence. The importance of a marketing information system for customer satisfaction: Provides useful hints or keys to an organization to get better and predict which can fulfill the needs as well as wants of customers so they will feel satisfied with what have done them before [29]. The utilization of MIS in big business positively influences key decision-making, enhancing the competitive position, and economic security of the business [30]. Effective MIS develops rationalized marketing and improves vital decision-making processes prompting enhanced profits for business [31].

As mentioned earlier also the objection of this research was to find the MIS factor's role in the performance of the company. The research findings go in line and confirm the result obtained [32], who found that record keeping is the most important factor in getting the information and managers consider it to be the most authentic and reliable source of information. The researcher [33] revealed the existence of a positive correlation between making use of and adopting marketing intelligence and the proper making of decisions, which this research work also approves. A researcher [34] found marketing decision support systems have a noteworthy effect on the performance of banking. This means there exists a positive link between market research and organizational performance.

Utilizing logistics MIS advances efficiency in logistics by enhanced cooperation and data transfer [35]. All this research gives ample evidence that the results obtained go in line with the above-mentioned literature hence it can be concluded that all the selected variables positively affect the performance of the logistics company directly.

5 Conclusion

Information systems, in various forms, are present in companies. However, it is more important that these systems are utilized to meet market demands effectively. MIS disseminates the flow of relevant information to managers, enabling them to make informed decisions related to market operations.

On the grounds of the research work, subsequent conclusions were written:

- The role of MIS in decision-making is important to the managers to give them an advantage over the competitors. Certainly, MIS makes a significant contribution to company performance. In particular, within logistics, MIS enhances performance through optimizing packaging operations, streamlining the transportation system, managing stock effectively, and improving the overall supply chain management. This results in better company efficiency, lessened costs, and customer satisfaction.
- The performance of the company is improved by all independent factors. Thus these factors enhance the performance and productivity of logistics companies by improving the flow of information, optimizing inventory control, streamlining transport, and enhancing warehouse

efficiency which results in a substantial increase in operational efficiency.

To sum up, if the company implements strong MIS, it would be a great help in increasing the efficiency of Nagpur logistics companies by providing information on changing market trends, customer preferences, and optimization of operations. These firms can use their MIS to make decisions driven by data, streamline their supply chain activities, and improve the way they connect with customers so that the company as a whole performs better than others and has a chance to win the competition. Robust MIS frameworks are critical in assisting logistics enterprises to rapidly adjust to emergent market developments and sustain competitive advantage in an ever-changing business environment.

6 Future scope of research

It will be helpful to repeat this examination in another setting. It is additionally strongly recommended that future investigators examine each component of MIS independently to focus more on explicit issues identified with each part.

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Mapping key performance indicators for sustainable hospital waste management

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Keywords: key performance indicators, hospital waste, hospital supply chain, sustainability, performance measurement.
Abstract: The increase in population has led to an increasingly important role for healthcare and, consequently, an increase in medical waste. Medical waste requires special care due to its capacity to transmit diseases. Therefore, evaluating the performance of a given hospital waste supply chain through certain performance indicators plays an especially important role in supply chain management. A literature review was therefore carried out about the hospital waste supply chain and its performance indicators. The main objective of this article is to analyze which performance indicators for hospital waste supply chains exist and what their impact is through the analysis of some case studies. A qualitative and quantitative analysis of existing publications on this subject was also carried out using the Scopus database with the keywords "key performance indicators" and "supply chain". From this study it can be seen that 2023 was the year with the highest number of publications, and the lowest number of publications was in 2011. Article is the typology with the highest number of publications, with more than 50% of the total.This study shows that performance indicators enable better decision-making in order to improve the efficiency of a hospital waste supply chain.

1 Introduction

The progress made in healthcare, the growth of the population and the expanding number of medical facilities have led to an increasing production of medical waste, which has also led to an increase in the importance of analyzing healthcare-related waste management [1]. The healthcare sector is a crucial component of the world economy, focusing on improving the experience of care, the health of the population, while reducing the costs associated with healthcare [2].

Health services contribute to the control, prevention and treatment of diseases, and are a sector that contains a substantial amount of financial and human resources, creating a large amount of material and waste, thus affecting environmental sustainability [3].

Healthcare-related waste is medical or biomedical waste resulting from all activities performed in healthcare establishments, research centers and laboratories associated with healthcare procedures [4,5]. One of the main objectives of a healthcare facility is to provide a secure and trustworthy healthcare waste management system. Hospital waste can affect people's health, as it can be infectious, toxic, lethal because of the potential to transmit disease [6]. In addition to providing healthcare to people, healthcare facilities generate infectious and non-infectious waste that affects the health of healthcare workers, patients and the population [7].

Supply chain management is critical to a company's ability to remain competitive in the global scale, with the challenge of identifying the most effective way to meet customer needs at the lowest cost [8]. The proper management of healthcare waste can potentially control the transmission of serious diseases that threaten human health and the environment, as well as avoid wasting energy and reducing costs [9]. Hospital supply chains face economic, environmental and social challenges [10].

Performance measurement plays a vital role in hospital management and there have been an increasing number of studies to evaluate healthcare performance [11]. A adequate performance measurement provides the information needed for a better decision-making [12].

The article looks at performance indicators related to the health sector and assesses their impact by analyzing case studies related to the central theme. The article provides a range of contributions to the health sector, including the following:

- An increase in both theoretical and practical knowledge of the key performance indicators of hospital waste supply chains.

- Improving decision-making and the appropriate selection of key performance indicators.

This article is divided into 5 sections. Section 1 presents an introduction to the central themes. Section 2 discusses the hospital waste supply chain and some concepts and also presents the performance indicators in hospital waste supply chains and their impact on them with some case studies relating hospital supply chains and hospital waste. Section 3 presents the methodology carried out throughout this study. Section 4 presents a quantitative and qualitative study using the Scopus database in order to analyze the publications already published in the area. Section 5 presents some conclusions drawn from the study.

2 Literature review

2.1 Hospital/healthcare waste supply chain

The healthcare supply chain has been evaluated in a different way to the standard supply chain due to its high level of complexity [8]. The healthcare sector is a major factor in environmental pollution, generating large amounts of waste, consuming a large amount of energy and emitting greenhouse gases [13].

Healthcare-related waste includes all the materials generated in healthcare centers, research centers, medical laboratories, but also healthcare-related waste generated at home [14]. Among all the waste generated, the waste considered hazardous for health professionals and patients is between 10 and 25% of the total medical waste [5]. A contaminated needle used incorrectly has a risk of 1 in 3 of developing hepatitis B infection, 1 in 30 of hepatitis C infection and 1 in 300 of HIV infection [15].

Sustainable Supply Chain Management (SSCM) in the medical sector involves the management of the flow of materials, services and information from suppliers to healthcare suppliers [13].

Table 1 presents the different types of solid medical waste and gives some examples.

Table 1 Types of solid HCW [16]

Solid Healthcare waste	
Cytotoxic	Drugs used in cancer therapy
Pharmaceutical	Expired and unused drugs
Sharps	Syringes with needles; blades; scalpels
Infectious	Blood and other body fluids; laboratory cultures
Chemical	Laboratory reagents; disinfectants; batteries
Radioactive	Sealed sources; absorbent paper; swabs
Pathological	Human tissues; organs or fluids; body parts

Due to mishandling and inadequate treatment, the management of healthcare waste in developing countries is a public health and environmental problem [17]. In addition, the use of disposable devices in developed countries is increasing due to the use of advanced technological practices and safety concerns, leading to an increase in waste generation in these countries compared to developing countries [18].

The storage of hospital waste in health centers and the transport of these materials to treatment centers are two risky tasks, involving risks for health professionals and people in the community [19]. Proper management of medical waste, avoids being a danger to health professionals and the general population, but also to the environment [5].

Figure 1 illustrates an example of a medical waste supply chain.

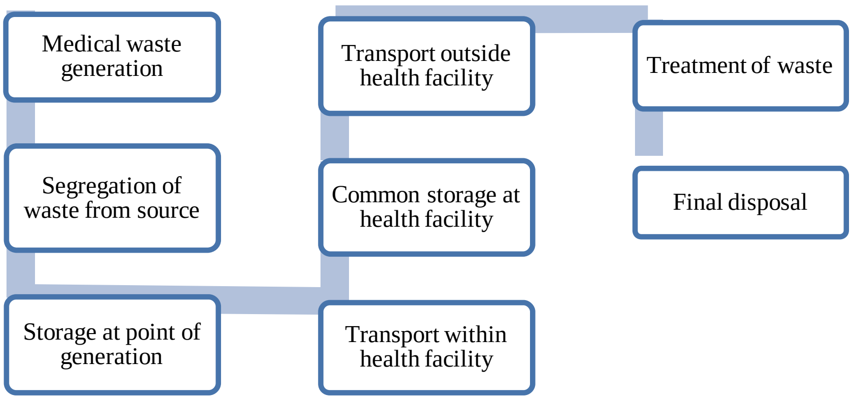

Figure 1 Example of Hospital medical waste chain [20]

The separation of hospital waste is an important step in the correct management of healthcare waste and the analysis of the composition of the waste makes it possible to determine the most appropriate methods for the disposal and treatment of healthcare-related waste [21].

Good waste management practices are best achieved by preparing and implementing a Health Services Waste Management Plan, describing all the steps and strategies according to each type of waste and containing actions to prevent possible impacts on public health and the environment [22]. The sustainable disposal of hospital waste is a field that requires further study due to its significant importance [23].

Faced with the negative effects that inadequate treatment of medical waste has on people, including environmental, economic and social issues, cities with higher population density need to find and develop a reliable medical waste management system [23].

2.2 Key performance indicators in healthcare

The instability of the environment and the dynamic changes taking place in world economies lead to the necessity of implementing and using new tools, such as the identification and implementation of indicators (KPIs) in the evaluation system, which make it possible to develop and improve organizations [24].

KPIs correspond to a quantitative index that shows the main success factors of a certain organization, and is adjusted to the context and objectives of each organization [25]. KPIs are considered to be management tools that allow management decisions to be planned, supported and controlled, making it possible to ensure the desired performance [26].

Performance indicators are used by hospitals to monitor and evaluate performance in relation to the values of other similar organizations or reference values, making it possible to ascertain whether performance is at the right level and to identify where improvements can be implemented [27,28].

An efficient and rational healthcare performance measurement system makes it possible to improve the quality of medical services, reduce costs, optimize service processes and obtain the best allocation of resources [11]. Evaluation of the healthcare sector is complex, since unsatisfactory performance can result from long waiting times, inefficiencies, patient dissatisfaction and burnout among healthcare professionals [29].

Table 2 contains examples of performance indicators related to hospital waste supply chains, divided into 4 types.

Table 2 Performance indicators and definition [30,31]

Typology	Indicator
Operational	Hospital Waste per Bed: Quantity of Hospital Waste produced per month/total number of existing beds
	Hospital Waste Production per Surgery: Quantity of Hospital Waste produced per month/total number of surgeries occurring in the operating room per month
	Production of Hospital Waste per External consult: Quantity of hospital waste produced per month/total number of outpatient visits per month
	Water Consumption per Sterilized Material: Consumption of H20 in the sterilization center per month/quantity of sterilized surgical instruments per month
	Water Consumption per Packaging Material: Consumption of H20 in the sterilization center per month/quantity of packaging material used in the sterilization center per month
	Electricity Consumption per Hospital Waste produced per month: Consumption of electricity per month/amount of hospital waste generated per month
Management	Containers collected per Employee: Number of containers collected/area where containers collected by each employee assigned to the waste collection per month/total building area
	Container collected per area: Number of containers collected by each employee assigned to the waste collection per month/total building area
Economic	Cost of Hospital Waste per bed management: Cost of hospital waste management collected and sent by external entity for final treatment per month/total number of existing beds
	Cost of Hospital Waste/Employee management personnel: Cost of personnel assigned to waste management per year/number of employees
Environmental	Total common healthcare waste (kg)/Total healthcare waste (kg)
	Cost of healthcare waste removal (bed)/Cost of healthcare waste removal (liters)
	Recyclable healthcare waste (kg)/Common healthcare waste (kg)

2.3 Key performance indicators for hospital waste supply chain – case studies

This section analyzes some case studies that show the use of performance indicators for hospital waste supply chains.

The case study carried out by Burlea-Schiopoiu & Ferhati [32] focuses on identifying a range of key performance indicators (KPIs) to enable managers and employees to assess, monitor and control the crucial factors influencing the performance of the healthcare sector in Algeria. The results show that the proper implementation of KPIs allows managers to make better decisions and are also used as tools for the developing of sustainable health systems both in Algeria and in developing countries.

In the case study presented by Ferronato et al. [33], the purpose is to present a proposal for a tool for integrated management as a first method of assessment to detect the predominant problems in a healthcare waste management system in Bolivia. The results prove the usefulness of applying indicators to analyze the priorities that should be considered in order to improve the healthcare waste management system.

Another case study carried out by Amos et al. [1], the objective is to define key performance indicators to increase the performance of waste management services in public hospitals in Ghana. Thus, data was collected and analyzed through interviews in hospitals and a general questionnaire survey, and then structural equations were modeled by partial least squares to model the relationships between the performance variables. A balanced scorecard was also used to categorize the performance variables. The results show a significant influence of the strategic quality and internal business indicators on waste management performance.

A case study proposed by Tudor et al. [34], this paper shows the results of two organizations - Cardiff and Vale NHS Trust and Cornwall NHS Trust - in relation to the systems they have implemented to minimize waste. A number of systems implemented by the two institutions aimed at the sustainable management of waste streams were analyzed. The results demonstrate the need to develop and implement systems to develop best practice.

3 Methodology

Research methodology is the science that allows the analysis of how research is carried out from a scientific point of view, with the main objective of describing and analyzing the methods, clarifying and highlighting the limitations and resources [35].

The aim of this study is to investigate performance indicators for improving supply chains related to healthcare and its waste. A literature review was conducted to contextualize the central concepts of the study, such as hospital waste supply chains, as well as the importance and examples of performance indicators.

Figure 2 illustrates the methodology used throughout this study.

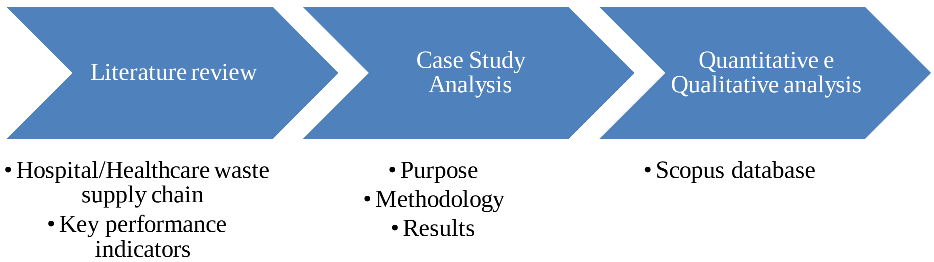

Figure 2 Research methodology

The case studies analyze the main objective of the work, the methodology used and the main results to be extracted from each case study. Through the analysis of various case studies, it is possible to investigate the different impacts and results that key performance indicators can have on supply chains.

Next, in the discussion section, the existence of publications related to the central theme of the study is analyzed in a qualitative and quantitative method with the support of the Scopus database, which investigates the concepts of “key performance indicators” and “supply chain”.

Finally, the conclusion section contains some of the conclusions drawn throughout the study and analyzes the importance of having performance indicators in hospital supply chains and hospital waste.

4 Result and discussion

Performance indicators allow organizations' performance to be monitored more carefully and make it possible to ascertain whether the results achieved make it possible to achieve the objectives set by the organizations. From the indicators, which are measured quantitatively, it is possible to analyze which areas need the most improvement.

Therefore, this section carries out a qualitative and quantitative analysis using the Scopus database in order to investigate the existence of publications relating performance indicators and supply chains with the criteria:

(“key performance indicators” and “supply chain”).

The following selection criteria were used to analyze documents related to the central theme of the study:

Research date: 27th May 2024
Research fields: "Article title, Abstract, Keywords"
Time period: Between 2010 and 2023
Language: English
Document Type: Article, Conference Paper, Book Chapter, Review, Conference review and Book

Figure 3 provides the number of results for each stage of the selection criteria.

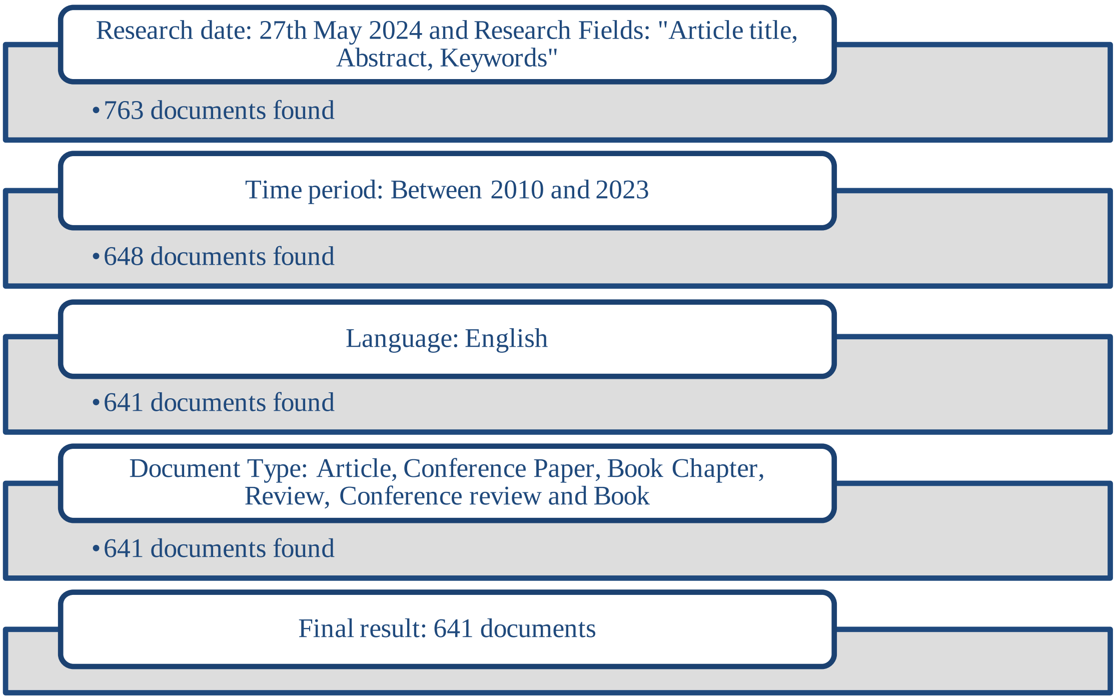

Figure 3 Number of documents found in each stage

Figure 3 shows that 763 documents were found in the first stage. When the search period was limited, the number was reduced to 648 documents. Seven documents whose language was not English were eliminated. Then, when the type of document was selected, the value did not change. Thus, the final result of the search was 641 documents.

Number of documents by year

Figure 4 presents the number of documents in each year.

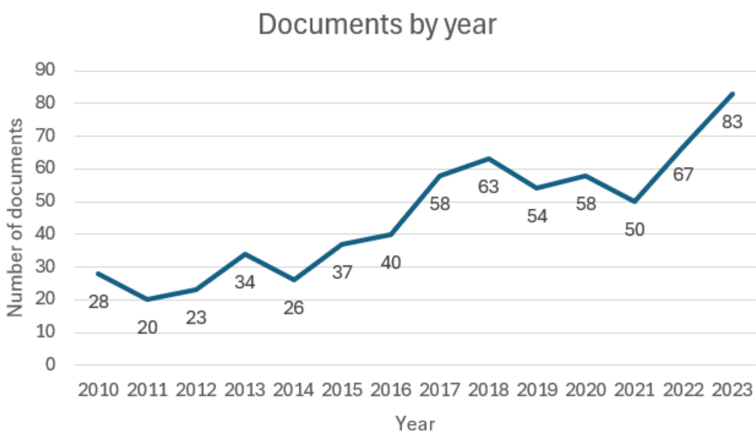

Figure 4 Number of documents in each year

Figure 4 shows an evolution in the number of publications using the concepts "key performance indicators" and "supply chain", with the minimum number being 20 in 2011 and the maximum number being 83 publications in 2023.

Number of documents by country

Figure 5 shows a map of the number of publications in each country. It should be noted that the higher the color density, the higher the number of publications in that country.

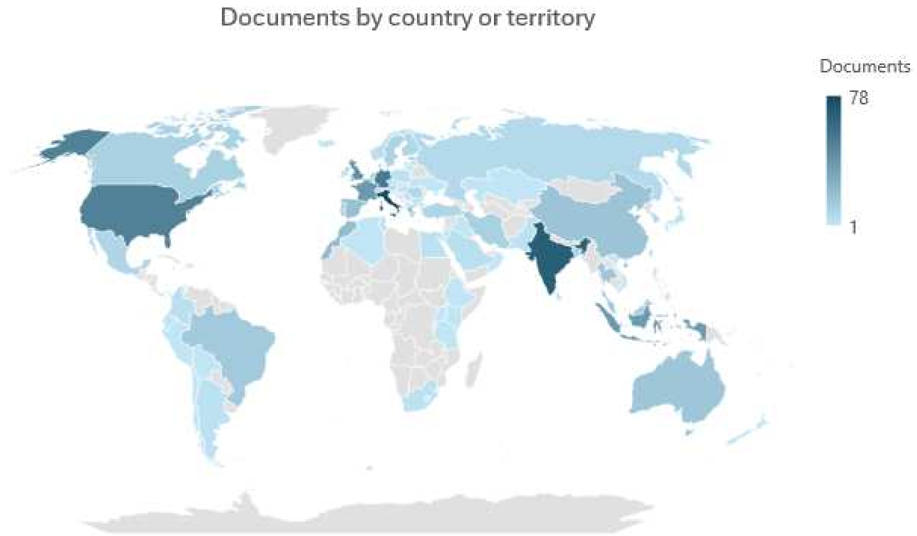

Figure 5 Number of documents by country/territory

Figure 5 illustrates that countries such as Italy, India, Germany and the United States have the highest number of publications on supply chain and performance indicators. There are also fewer publications on the African continent than in the rest of the world. Practically all European countries have published in this area.

Number of documents by type

Table 3 shows the number of each type of publication. Figure 6 shows the distribution of the type of publications with the respective percentages.

Table 3 Number of documents by type

Document Type	Number	Document Type	Number
Article	322	Conference Paper	246
Review	23	Book Chapter	40
Conference Review	8	Book	2

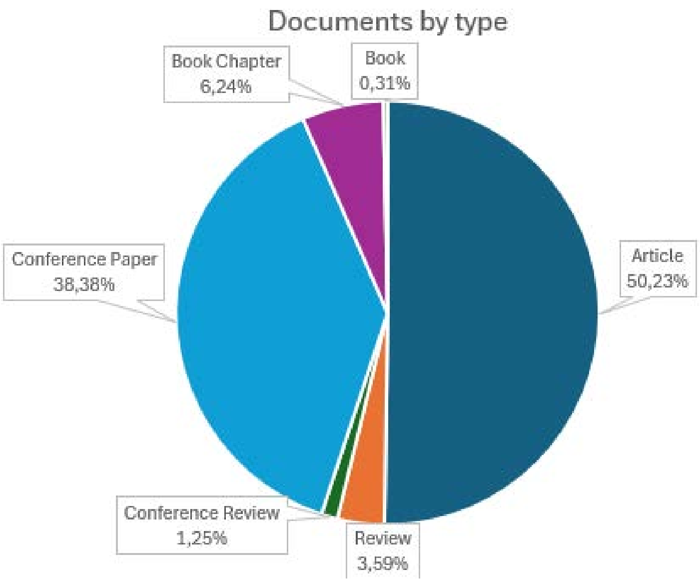

Figure 6 Number of documents by type

Table 3 and Figure 6 show that Articles and Conference Papers have the highest number of publications (together with 568 publications - 88.61% of all existing publications). Article is the typology that has more than half of the existing publications (around 50.23%).

Keyword Analysis

A study was also carried out looking at the keywords present in the publications in this study.

Figure 7 provides a visualization of the network which shows a graphic representation of the relationships between the keywords present in the set of documents under analysis. It should be noted that only keywords with at least 5 occurrences were used in this analysis.

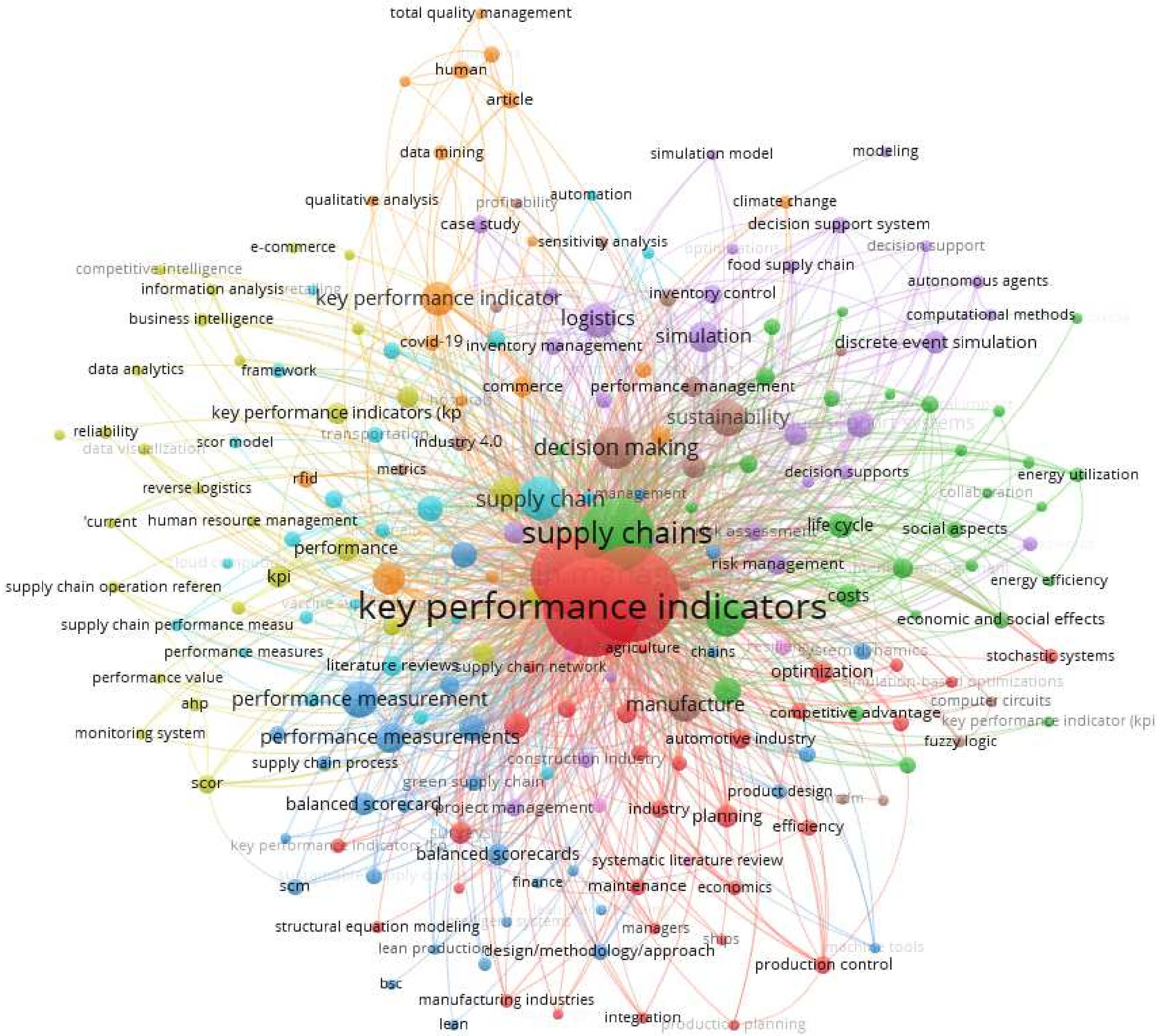

Figure 7 Network visualization

Figure 7 shows different colors representing different clusters. There are 9 clusters in this network with a total of 212 keywords. The most occurring keywords are "key performance indicators", "benchmarking", "supply chain management" and "supply chains". It should be noted that the larger the size of the letter, the higher the number of occurrences. The high number of occurrences of these keywords in the different publications shows the importance of this topic for researchers.

5 Conclusions

The main purpose of this study was to analyze the importance of performance indicators in hospital waste supply chains. Thus, a contextualization of the main concepts of this study was carried out and some case studies were analyzed, allowing for an analysis of the importance of performance indicators in hospital waste supply chains.

A quantitative and qualitative study was then carried out using the Scopus database, which showed an increase in the number of publications over the years and the existence of documents related to the subject on practically every continent (the smallest number on the African continent).

According to the results presented in the "Results and discussion" section, there has been an increase in the number of publications over the year, with 2023 being the peak year in terms of the number of publications. Countries such as Italy, India, Germany and the United States are the main ones responsible for the largest number of publications. The type of documents with the highest number of publications are articles, with 322, and conference papers with 246.

The increase in population has led to an exponential rise in medical waste generated by health institutions due to the need for more healthcare. If this waste is not treated correctly, it can have negative consequences for society. In this way, the implementation of performance indicators in hospital waste supply chains allows for better planning, monitoring and evaluation of the objectives proposed by organizations. Areas related to the health sector must be constantly analyzed, as it is one of the most important sectors for society.

As future work, it is necessary to carry out more case studies that show the importance of implementing performance indicators to improve the performance of hospital waste supply chains; to analyze the environmental, social and economic impact of hospital waste management.

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Mathematical optimization model for remanufacturing scheduling with sequence-dependent setup times

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Abstract: Remanufacturing is a key player in supporting sustainable manufacturing methods, a regenerative economic model, and the equitable allocation of resources in the ever-evolving environment of sustainable development. Our study tackles the scheduling difficulties in remanufacturing to facilitate sustainable practices. Specifically, we concentrate on scheduling operations on a mixed assembly/disassembly line, taking into account sequence-dependent setup time to minimize makespan, considering its substantial impact on remanufacturing efficiency. This work explores a crucial scheduling problem in hybrid production lines, concentrating on a mixed-flow job-shop structure. These systems provide an NP-hard scheduling challenge since they have two types of operations that need to be processed through the same group of workstations in different directions. Our main goal is to reduce the makespan or the maximum amount of time it takes to complete all the jobs. A mixed integer linear programming model (MILP) specifically addresses the complexities of this remanufacturing scheduling problem. Our goal in using this method is to find the best solutions for different cases while giving priority to processing efficiency. Extensive testing results confirm the effectiveness of our proposed mathematical framework, showing it can consistently provide outstanding performance in various scenarios. In this work, the implementation of modified scheduling methodologies to meet sustainable development goals expands the study of remanufacturing scheduling. It also highlights areas that may require more research, such as integrating logistics and improving the energy efficiency of remanufacturing processes.

1 Introduction

Over the past few decades, resource extraction and consumption have tripled due to a considerable rise brought on by simultaneous increases in consumption, population growth, and economic development [1]. In addition, the waste output is increasing due to technological improvements resulting in shorter product life spans [2]. To slow the rate of environmental deterioration, we must make significant changes to how we consume and conduct business [3]. This entails establishing innovative strategies to reduce the use of energy and resources, as well as adopting sustainable practices that encourage the reuse of materials, the use of renewable energy sources, and energy-efficient operations [4]. Because of this, sustainability has become legendary in today's world, where climate change is the norm due to mounting social pressure and environmental concerns [5-7]. Sustainable development represents a promise of a better world without compromising the environment for future generations. The circular economy is considered a viable tool to achieve economic sustainability, as it aims to bring the industry back into harmony with the environment. As a result, the movement towards a circular economy represents a significant opportunity to reconsider the relationship between production, consumption, and resources. Moving to a circular paradigm involves changing the economic logic from the traditional linear supply chain to a closed-loop supply chain in which, in addition to the usual direct flow of goods (from material sourcing to production to distribution), a reverse flow of goods back to the manufacturers takes place [8].

To effectively close the supply chain loop, all essential elements must be involved, from suppliers to manufacturers, distribution centers and customers, collection and return centers, product and component recovery systems, and waste and polluting components disposal facilities. There have been significant advances in reverse flow research over the past few years, with much of it focusing on the movement of goods back into a supply chain [8]. In the traditional supply chain, the product flow moves from the supplier to the plant, and the finished items are sent out to the customers. With the introduction of reverse flows, end-of-life goods are being returned from end destinations (usually customers) back to the manufacturers, who either reintroduce them into the manufacturing system to be remanufactured or dispose of them responsibly in a waste treatment facility.

In the circular economy, remanufacturing plays a crucial role in maintaining the functionality and performance of products after their end-of-use/life. This is achieved by recovering the value of used products by reusing and recovering components and using them to produce new or like-new products [9]. Remanufacturing not only extends the useful life of products but also reduces the amount of waste materials entering the waste management system. Simultaneously, remanufacturing presents manufacturers worldwide with opportunities to make significant savings in materials and energy, minimize the amount of waste generated, and boost employment while bringing products of impeccable quality at lower cost into the market.

As industries increasingly adopt sustainable practices, the importance of efficient scheduling in remanufacturing processes has grown. Scheduling is an approach used to optimize manufacturing processes in order to enhance the performance of a given system or to get closer to its optimality in a short period of time (short-term schedule). Scheduling in remanufacturing is complex due to the variability in product conditions, the need for inventory management, and the integration of disassembly and assembly tasks. Therefore, proper scheduling and execution of remanufacturing operations such as disassembly and reassembly would make a significant impact in terms of achieving sustainability, cost savings, and resource conservation [10]. Since assembly and disassembly are key processes in remanufacturing, the concept of hybrid assembly and disassembly lines has gained significant attention due to the increasing need for efficient production systems that can adapt to both manufacturing and remanufacturing processes. Hybrid systems integrate assembly and disassembly tasks, allowing for a more flexible approach to production that can accommodate the complexities of modern manufacturing and sustainability goals. A hybrid assembly/disassembly line is characterized by its ability to perform both assembly and disassembly operations using shared workstations and resources. This integration is essential for optimizing productivity and resource utilization in remanufacturing environments.

Most studies in the technical literature on remanufacturing scheduling deal separately with assembly and disassembly scheduling problems. Only a few articles consider integrated assembly and disassembly and the possibility of using the same lines and equipment for both processes, such as the studies proposed by [11] and [12], which present hybrid systems for assembly and disassembly that can also be applied for remanufacturing processes. The integration of mixed disassembly and assembly operations on a single remanufacturing line assumes that the sequence of disassembly operations is precisely the inverse of the sequence of assembly operations.

Featuring dual workflows, this hybrid remanufacturing line is typical of a job-shop configuration or the confluence of two parallel flow shops, where one is dedicated to assembly with a direct flow and the other to disassembly with a reverse flow. To better understand this proposed mixed assembly/disassembly line model, Figure 1 provides a visual representation of its structure and components. In order to provide a clearer understanding of how the system operates, let us examine a hypothetical product consisting of three distinct components or subassemblies, denoted as A, B, and C. The product is sequentially assembled, first with part A, followed by part B, and concluding with part C, so replicating the workflow of an assembly line. On the other hand, when disassembling, it is presumed that components are taken out in the exact opposite order of their assembly. This means starting with C, then B, and lastly, A. To further illustrate this concept, consider the example of a computer hard drive. The assembly process involves attaching the printed circuit board (A) to the casing, followed by placing the platters (B) onto the spindle, and finally securing the top of the casing (C). Disassembly follows the reverse order, starting with removing the casing (C), then lifting the platters (B), and lastly detaching the printed circuit board (A). This practical example mirrors the sequential assembly and reverse disassembly process outlined in the model, highlighting its applicability to real-world scenarios. This hybrid line aims to effectively disassemble components and sub-assemblies from used items and eventually reassemble new remanufactured products.

Recent works have additionally focused on producing more realistic mathematical models by taking into account a range of parameters and constraints, including availability constraints, learning effects, deterioration effects, transportation, resource consumption, and sequence-dependent setup times [13]. Consequently, the literature has yet to investigate the integration of sequence-dependent setup time in the context of a mixed assembly/disassembly scheduling problem. In practice, sequence-dependent setup times are of significant importance when transitioning from one operation to another, as different setup times may be necessary to complete a specific sequence of assembly and disassembly operations. The growing need to take into account sequence-dependent setup times in order to achieve optimal and relevant scheduling is, therefore, motivating research efforts in this field.

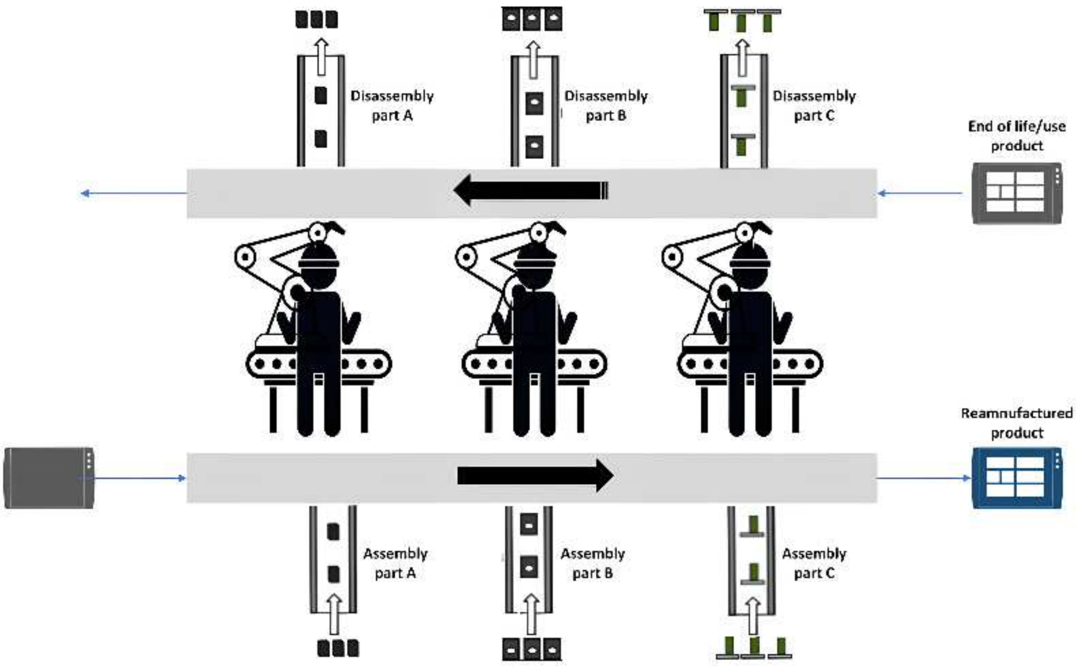

Figure 1 Schematic representation illustrating the setup of a combined assembly and disassembly line

The current study aims to create a resolution approach to remanufacturing operation scheduling that will maximize operational efficiency by successfully addressing the different aspects of this hybrid remanufacturing line. Our paper explores a relatively unexplored area of research, namely how to efficiently schedule two key remanufacturing processes, disassembly and assembly, to minimize the makespan while considering sequence-dependent setup time between assembly and disassembly operations. This research explores how remanufacturing processes affect circular economy principles and the quest for sustainability. At present, this particular approach to remanufacturing scheduling and the proposed mathematical formulation for its resolution address an important gap in the existing literature on remanufacturing scheduling, highlighting an innovative aspect of crucial importance for future research on this topic.

To resume, this paper presents two key contributions to the field of remanufacturing:

- This study introduces a hybrid line system for remanufacturing end-of-life/used products designed to optimize both assembly and disassembly processes.
- The research proposes a Mixed Integer Linear Programming (MILP) model to solve the scheduling problem of assembly and disassembly operations optimally while considering sequence-dependent setup time.
- The proposed MILP model offers an optimal solution for minimizing makespan and maximizing resource utilization on the hybrid line, contributing to more sustainable and cost-effective remanufacturing practices.

The remainder of this paper is presented methodically to present the various facets related to this remanufacturing scheduling problem. Section 2 presents a review of the available literature highlighting the importance of addressing this challenge. A detailed description of the problem studied, and its mathematical formulation is given in Section 3, aimed at providing optimal solutions for small and medium-sized instances of the problem, and in Section 4, we validate the proposed MILP model, providing test results that are also discussed. Finally, we present our conclusions in Section 5, summarizing our main contributions to the field of remanufacturing scheduling and their implications for both academic research and practical applications, as well as proposing potential directions for future exploration in this dynamic area.

2 Literature review

It is increasingly agreed that moving from the present linear industrial model to a circular economy is the key to achieving sustainable production and development, thereby creating a more sustainable and environmentally aware society. Transitioning to a circular economy involves rethinking traditional manufacturing processes and product life cycles to prioritize sustainable development. The challenge of achieving sustainability is, in general, a complicated process requiring numerous considerations, including technology and engineering, the environment, economics, human health and well-being, community aspirations, as well as public policy, procedures, and strategies [14,15]. This multifaceted approach ensures that sustainable practices are integrated at every industrial and societal development level.

Sustainable manufacturing as a whole relates to technical and organizational approaches that contribute to developing and implementing innovative manufacturing methods, designs, processes, and technologies to overcome the global scarcity of resources, reduce excessive environmental impact, and achieve environment-friendly product life cycles [16,17]. These innovations are crucial in driving the shift towards cleaner production practices. Sustainability in manufacturing encompasses all the stages of the product life cycle: design, pre-manufacturing, producing, usage, and post-utilization (reduce, reuse, recycle, recover, redesign, and remanufacture) [18,19]. By considering each stage of a product life cycle, manufacturers identify opportunities to minimize waste and enhance resource efficiency.

Furthermore, today's market is characterized by a growing demand for better-quality customized products, which can be obtained at the lowest cost in the shortest possible time. This production, which responds to the strong demand for new and customized products, results in enormous quantities of obsolete products that contain significant amounts of renewable resources. This paradox highlights the need for effective strategies to manage product obsolescence and resource recovery. Along with the increased environmental protection regulations [20], the increasing demand for environmentally friendly products [21] as well and the urge to take social responsibility [22], manufacturers are actively seeking new approaches to the way they operate their activities, which led to consider the return and the recycling of products at the end of their useful lives for reuse, recycling of materials, remanufacturing of products, reuse of component. Hence, the new kind of physical flow in the supply chains, known as reverse flows [23,24]. These reverse flows represent a significant shift in managing supply chains, prioritizing sustainable practices.

The most forward-thinking companies see the opportunities presented by this evolving landscape as a new revenue stream. For instance, item segregation or disassembly (i.e., the separation of a part or group of parts from an assembly using a reverse assembly flow) has been facilitated by the development of disassembly technologies and the creation of product designs that take specific consideration of disassembly requirements [25]. These developments lessen waste production and the carbon impact by simplifying recovering and reuse of valuable components of end-of-life/use goods.

Components can be repurposed, refurbished, or saved for later use after being disassembled. By decreasing waste and optimizing resource consumption, these strategies help to create an economy with greater circularity where resources are continuously cycled through the system. These initiatives also help the company's sustainability objectives and improve its reputation. As a result, businesses get a competitive edge in the market in addition to environmental benefits. To take full advantage of these prospects, businesses also need to deal with the challenges of scheduling these processes. The process of scheduling encompasses multiple layers of constraints, each of which requires special attention in order to guarantee effective operations and the most effective allocation of resources. Thus, enhancing profitability and operating efficiency, as well as lowering energy and resource consumption, all depend on effective scheduling in the remanufacturing sector [26]. As for assembly scheduling [27,28], there are numerous studies on disassembly scheduling issues, including [29,30], and [31]. However, integrating these two scheduling processes remains to be explored.

Given the complexity of remanufacturing activities, the topic of combined assembly and disassembly processes has obviously attracted some attention, as can be deduced from the works of [11,12,32,33]. Indeed, these research papers have laid the foundations for understanding an integrated production system's complexities and potential efficiencies. Although a fundamental framework exists for the application of mixed assembly and disassembly lines, significant gaps remain when it comes to addressing the inherent multifaceted challenges of scheduling the processes of these systems. Addressing these challenges requires innovative scheduling solutions that can adapt to the dynamic nature of hybrid production systems. An adjustment or setup operation often occurs in many real situations while moving between operations, hence the importance of considering setup times. Scheduling problems on the shop floor involving sequence-dependent setup times are encountered in numerous real-world situations, such as in the aerospace, printing, and semiconductor manufacturing industries [34,35].

To sum up, this hybrid assembly/disassembly line scheduling problem requires complex coordination of assembly and disassembly jobs, carefully considering the setup times associated with each type of job, especially given their sequence-dependent nature. The primary goal in solving this problem is developing an optimal scheduling plan for the jobs on the equipment with the aim of lowering the maximum completion time, or makespan. Reaching this goal is essential to improving remanufacturing businesses' overall efficiency.

3 Problem description and formulation

In the context of this remanufacturing setup, n jobs with known processing times are ready to be processed at time 0, across m workstations denoted as $\boldsymbol{M_1}, \boldsymbol{M_2}, \dots, \boldsymbol{M_m}$, with each job being treated on its assigned workstation, without interruption. These jobs have two possible flows:

- For the assembly process: a set of assembly jobs $\boldsymbol{E_A} = \{\boldsymbol{J_1}, \boldsymbol{J_2}, \dots, \boldsymbol{J_a}\}$ are processed following a direct flow from $\boldsymbol{M_1} \rightarrow \boldsymbol{M_2} \rightarrow \cdots \rightarrow \boldsymbol{M_m}$.
- For the disassembly process: a set of disassembly jobs $\boldsymbol{E_D} = \{\boldsymbol{J_{a+1}}, \boldsymbol{J_{a+2}}, \dots, \boldsymbol{J_n}\}$ are processed following a reverse flow, i.e., from $\boldsymbol{M_m} \rightarrow \boldsymbol{M_{m-1}} \rightarrow \cdots \rightarrow \boldsymbol{M_1}$.

This hybrid line scheduling problem is an NP-hard scenario that combines the constraints of sequence-dependent setup times with complicated assembly and disassembly processes. The term "setup time" describes the amount of time needed to prepare a resource for an operation, which may include activities like cleaning, modifying parameters, or switching out tools. The latter is a decisive factor in production efficiency, given that longer setup times can result in longer downtimes and lower productivity. Setup times are significant in real-world manufacturing and remanufacturing environments and can significantly impact the overall processing time or makespan.

In this framework, the setup time associated with a given job is not determined solely by the job itself; rather, it depends on the juxtaposition of this job with the one that precedes it. This dependency introduces a variable amount of transition time between successive jobs, which is intrinsically dependent on their sequence. For example, the time needed to configure the workstation to go from job 1 to job 2 may be very different from that needed to go from job 1 to job 5, regardless of the constancy of the workstation used. This additional dimension of variability considerably increases the complexity of this remanufacturing scheduling problem, requiring highly specialized scheduling strategies to optimize overall production efficiency and keep workstation downtime to a minimum. Also, one notable feature of this hybrid production line is the separable nature of these setup times, allowing the setup to begin as soon as a workstation becomes available (anticipatory setup). This characteristic significantly influences the efficiency of the scheduling process.

A mathematical formulation is presented to provide a precise and formal definition of the hybrid assembly/disassembly shop scheduling problem. This mixed-integer linear programming model includes an objective function that aims to minimize the makespan and a set of constraints that model the specific characteristics, constraints and requirements of this problem.

Let the following notations be defined:

Sets and Indices

- M: Set of all available workstations, $M = \{1, \dots, m\}$.
- J: Set of all jobs to be scheduled, $J = \{1, \dots, n\}$.
- P: set of positions, $P = \{1, \dots, p\}$, position of a job on the workstation.
- k: workstation index.
- j: job index.
- i: position index.
- $E_A = \{J_1, J_2, \dots, J_a\}$: set of assembly jobs.
- $E_D = \{J_{a+1}, J_{a+2}, \dots, J_n\}$: set of disassembly jobs.

Variables

- X_{kji}: Binary variable, equal to 1 if job j is assigned to workstation k at position i, 0 otherwise.
- $Y_{jj'}^{ki}, Y_{j'j}^{ki}$: Binary variables, equal to 1 if job $j \in E_A$ is followed by job $j' \in E_D$ on workstation k at positions $i, i+1$ or vice versa, and 0 otherwise.
- $t_{j,j'}$: Setup time between job j and job j′ when transitioning between assembly and disassembly operations on the same workstation k.
- p_{kj}: Processing time of job j on workstation k.
- s_{kj}: Start time of job j on workstation k.
- c_{kj}: Completion time of job j on workstation k.
- c_k: Completion time of all jobs on workstation k.
- C_{max}: Makespan.

3.1 Mixed-integer linear programming model

The objective function seeks to minimize the makespan, represented by equation (1), which is the completion time of the last job on the first or the last workstation:

$$Minimize\ C_{max} \tag{1}$$

The equations can be grouped into sets, and each group of equations corresponds to a type of constraint in the system. An explanation is given for each set of constraints:

Workstation and job assignment constraints:

$$\sum_{j \in n} X_{kji} = 1, \ \forall k \in M, i \in P \tag{2}$$

Equation (2) ensures that each position on every workstation is assigned to exactly one job from the set of all jobs. This constraint guarantees that no position on a workstation is left unassigned or assigned to more than one job.

$$\sum_{i \in p} X_{kji} = 1, \ \forall k \in M, j \in J \tag{3}$$

Equation (3) ensures that each job is assigned to exactly one position on each workstation and prevents a job from being processed in more than one position on the same workstation.

Assembly and disassembly sequencing constraints:

$$Y_{jj'}^{ki} = X_{kji} \times X_{kj'(i+1)}, \ \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{4}$$

$$Y_{j'j}^{ki} = X_{kj'i} \times X_{kj(i+1)}, \ \forall k \in M, i \in P - \{p\}, j \in E_A \tag{5}$$

Constraints (4) and (5) define the order of assembly and disassembly jobs. They ensure that if an assembly job j is followed by a disassembly job j′ on workstation k at position i and i+1, or vice versa, this order is correctly reflected in the variables $Y_{jj'}^{ki}$ and $Y_{j'j}^{ki}$.

Binary variable constraints for sequencing:

$$Y_{jj'}^{ki} \leq X_{kji},\ \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{6}$$

$$Y_{jj'}^{ki} \leq X_{kj'(i+1)},\ \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{7}$$

$$Y_{jj'}^{ki} \geq \left(X_{kji} + X_{kj'(i+1)}\right) - 1, \quad \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{8}$$

$$Y_{j'j}^{ki} \leq X_{kj'i}, \quad \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{9}$$

$$Y_{j'j}^{ki} \leq X_{kj(i+1)}, \quad \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{10}$$

$$Y_{j'j}^{ki} \geq \left(X_{kj'i} + X_{kj(i+1)}\right) - 1, \quad \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{11}$$

Equations (6) to (11) link the binary variables X_{kji}, $Y_{jj'}^{ki}$, and $Y_{j'j}^{ki}$. These constraints ensure that the sequencing binary variables Y are set to 1 if and only if both corresponding jobs j and j′ are assigned to consecutive positions i and i+1 on the same workstation k.

Start time constraints for assembly and disassembly jobs:

$$s_{1j} \leq M \cdot \left(1 - X_{1,j,1}\right), \quad \forall j \in E_A \tag{12}$$

Constraint (12) sets a large enough start time for the first job in the assembly jobs set if it isn't assigned to the first position on the first workstation.

$$s_{mj} \leq M \cdot \left(1 - X_{m,j,1}\right), \quad \forall j \in E_D \tag{13}$$

Constraint (13) is similar to the previous equation but for disassembly jobs. It sets the start time for disassembly jobs on the last workstation m.

Sequencing and setup-time constraints:

$$s_{kj} + p_{kj} + t_{j,j'} \leq s_{kj'} + M \cdot \left(1 - Y_{jj'}^{ki}\right), \quad \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{14}$$

$$s_{kj'} + p_{kj'} + t_{j',j} \leq s_{kj} + M \cdot \left(1 - Y_{j'j}^{ki}\right), \quad \forall k \in M, i \in P-\{p\}, j \in E_A, j' \in E_D \tag{15}$$

Equations (14) and (15) ensure the correct sequencing of jobs, including the sequence-dependent setup time required between them. These constraints define the relationship between start times, processing times, and setup times, accounting for the order of assembly and disassembly jobs.

Continuity of jobs constraints:

$$s_{kj} + p_{kj} \leq c_{kj}, \quad \forall k \in M, j \in E_A \tag{16}$$

$$c_{kj} \leq s_{(k+1)j}, \quad \forall k \in M-\{m\}, j \in E_A \tag{17}$$

$$s_{kj} + p_{kj} \leq c_{kj}, \quad \forall k \in M, j \in E_D \tag{18}$$

$$c_{kj} \leq s_{(k-1)j}, \quad \forall k \in M-\{1\}, j \in E_D \tag{19}$$

Since we have one direct and one reverse flow, constraints (16) to (19) ensure that for assembly jobs, the completion time on one workstation is before the start time on the next one, and for disassembly jobs, the completion time on one workstation is before the start time on the previous one.

Positional continuity constraints:

$$s_{kj} + M \cdot (1 - X_{kj(i+1)}) \geq p_{kj'} + s_{kj'} - M \cdot (1 - X_{kji'}), \qquad \forall j, j' \in J, k \in M, i \in P - \{p\} \tag{20}$$

Considering the processing times, constraint (20) ensures the continuity of job positions on each workstation.

Maximum completion time constraints:

$$c_k = max\{c_{kj}\}, \qquad \forall k \in M, j \in J \tag{21}$$

$$C_{\max} = max\{c_k\}, \forall k \in M \tag{22}$$

Equation (21) calculates the completion time of all jobs on each workstation k as the maximum completion time of individual jobs. Equation (22) defines the makespan as the maximum of these completion times across all workstations.

4 Results and discussion

To validate the efficacy of the proposed model, we conducted extensive computational experiments across various small and medium-sized instances with samples of processing times with a *U*(1.99) and setup times with a *U*(1.30) distribution in order to reflect the actual operating conditions in our test cases, giving a more realistic assessment of this scheduling challenge. The mixed-integer linear programming model developed for this study was solved using IBM ILOG CPLEX solver. This software is renowned for its efficient handling of linear programming, mixed-integer programming, and many other complex computational applications. The following is a sample instance that was solved effectively by our MILP model:

Consider, for instance, a workshop featuring a hybrid production line equipped with five workstations, denoted as $M_1, M_2, \ldots, M_5$. Three assembly jobs designated $J_1, J_2, and\ J_3$ are handled alongside three disassembly jobs $J_4, J_5, and\ J_6$. While the assembly operations traverse the line in a forward sequence from M_1, M_2, ...through M5, the disassembly operations undergo processing in reverse order, i.e., from M_5 to M_1.

An illustrative instance is presented to demonstrate the model's application, followed by a detailed solution analysis and a Gantt chart visualization. Table 1 tabulates the processing times for each job's operations, whereas Table 2 details the sequence-dependent setup times required when transitioning between assembly and disassembly jobs on the same workstation.

Our MILP model uses strategic sequencing of the operations across the workstations to mitigate lengthy setup times, which is essential to minimizing the overall production time (makespan). The Gantt chart (refer to Figure 2) provides a visual representation of the optimal schedule generated by the MILP model of the instance given as an example. Each row corresponds to a workstation, and each colored block denotes a job's execution on that workstation. The length of the block signifies the processing time, while any gaps between blocks indicate idle periods and the red segments represent the setup phase. To provide a comprehensive understanding of the schedule, let us examine the Gantt chart step-by-step.

Table 1 Processing times

	M_1	M_2	M_3	M_4	M_5
J_1	**51**	**47**	**18**	**95**	**35**
J_2	**59**	**62**	**27**	**81**	**26**
J_3	**87**	**56**	**75**	**13**	**36**
J_4	**75**	**91**	**54**	**73**	**51**
J_5	**52**	**37**	**29**	**13**	**63**
J_6	**20**	**64**	**58**	**20**	**48**

Table 2 Setup times

	M_1	M_2	M_3	M_4	M_5	M_6
J_1	**-**	**-**	**-**	**16**	**5**	**1**
J_2	**-**	**-**	**-**	**4**	**11**	**16**
J_3	**-**	**-**	**-**	**5**	**4**	**4**
J_4	**14**	**5**	**15**	**-**	**-**	**-**
J_5	**11**	**17**	**14**	**-**	**-**	**-**
J_6	**19**	**4**	**6**	**-**	**-**	**-**

Beginning with Machine 1, we observe that it initiates the assembly process by processing Job 1, followed by Job 2, and then 3. Once Job 3 is complete, the machine transitions to handle disassembly jobs after a setup operation, starting with Job 4, then Job 5, and lastly, Job 6. The red segments interspersed between these jobs represent the setup-time required when switching between assembly and disassembly operations. Moving on to Machine 5, it commences with Job 4 at time 0, succeeded by Job 5 and then 6. Subsequently, after the setup operation, it processes Job 2 from the assembly set, followed by Job 1, and finally, Job 3. The pattern continues similarly across the remaining machines, with each machine handling a mix of assembly and disassembly jobs based on their designated flow and the optimized schedule achieved by the MILP model.

The chart visually depicts the makespan, which is the total time required to complete all jobs, as 465.0 units. This detailed walkthrough of the Gantt chart underscores the model's ability to efficiently allocate and sequence jobs while considering setup time constraints and the hybrid nature of the assembly/disassembly line. Crucially, the chart showcases the model's strategic sequencing to minimize makespan. For example, on workstation 5, Job 5's operation precedes Job 6's, yet this order is reversed on workstation 4. This deliberate reordering stems from the varying setup times between different job combinations. By prioritizing the sequence with the shortest setup, the model effectively reduces overall production time. Similar strategic sequencing is evident for Jobs 1 and 2 on workstations 2 and 3.

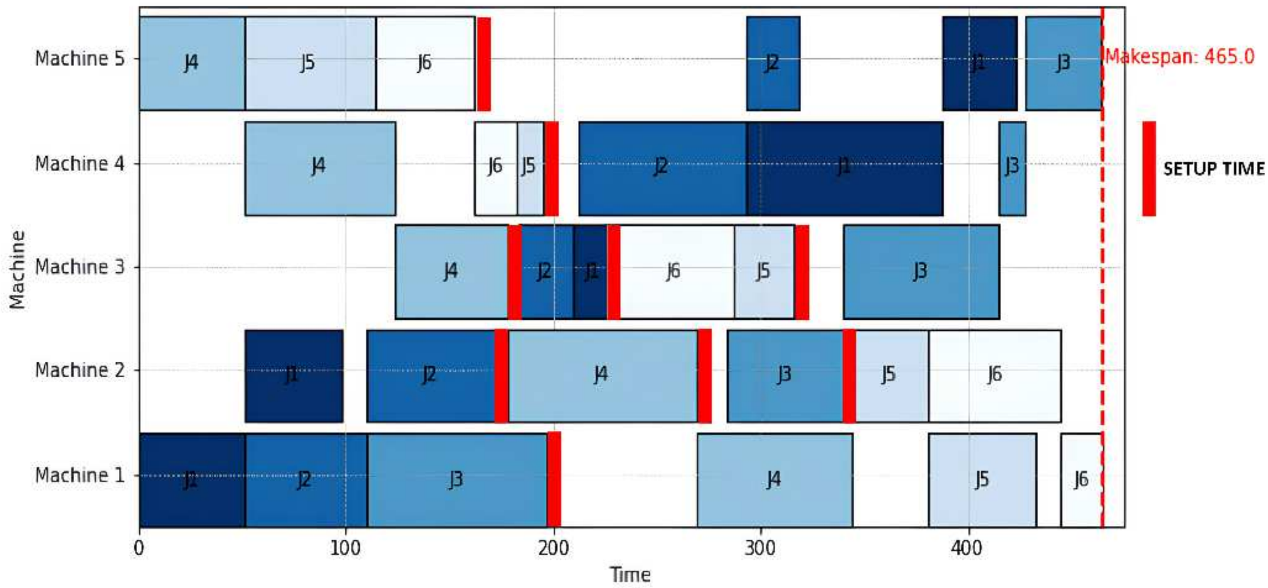

Figure 2 Gantt chart of the sample instance

This purposeful reordering is motivated by the different requirements of subsequent jobs, leading the model to seek out the optimal sequence that requires the shortest applicable setup time. These sequencing decisions underline the MILP's ability to take careful account of setup times between jobs. While the MILP model proved its effectiveness in solving the problem faced by small and some medium-sized instances, it encounters significant computational limitations as the size of the problem increases. The complexities of larger instances lead to an exponential increase in computational time, thus preventing the MILP from providing timely solutions for large-scale applications. The execution of the MILP for small and medium-sized is carried out quickly, and the results are available immediately. When running the mathematical model for larger instances, it took, in many cases, over three hours to successfully run the model with 20 jobs/3 workstations instances and over 12 hours to execute the problem with 20 jobs/5 workstations using the model proposed. So, the bigger the instance, the longer it takes to solve the problem.

5 Conclusion and perspectives

Efficient scheduling in remanufacturing is essential for maximizing resource allocation and improving efficiency, and this study contributes to the field of remanufacturing optimization by developing and validating a mixed-integer linear programming (MILP) model for scheduling hybrid assembly/disassembly lines with sequence-dependent setup times, an aspect that has not been adequately addressed in the existing literature. This model offers an effective strategy for optimizing small and medium-sized instances of this NP-hard problem, potentially leading to improved resource allocation, reduced costs, and enhanced sustainability in remanufacturing facilities. The MILP model's efficacy was demonstrated through computational experiments showcasing its ability to generate optimal schedules. The Gantt chart visualization further highlighted the model's strategic sequencing of jobs to minimize makespan and effectively manage the complexities of the assembly disassembly hybrid line. Nevertheless, the research also acknowledges the computational limitations of the MILP model when dealing with instances of significant scale. This limitation highlights the need for further exploration into advanced optimization techniques and algorithms that can efficiently handle the complexities of larger remanufacturing systems.

Future work could focus on developing and evaluating advanced algorithms that can efficiently tackle large-scale hybrid assembly/disassembly scheduling problems. These algorithms could incorporate techniques like decomposition, relaxation, or machine learning to enhance computational performance. The current model could be extended to include additional real-world constraints, such as machine breakdowns, uncertain processing times, parts transportation, or multiple product types. Such extensions would further enhance the model's applicability and practicality. Furthermore, exploring the integration of this scheduling model with Industry 4.0 technologies, such as real-time data collection and analysis, could enable dynamic scheduling and further optimize production processes. By taking these directions, a more holistic grasp of remanufacturing systems can be achieved, which is of growing relevance in the context of resource scarcity and the global drive towards more environmentally friendly manufacturing practices. As such, this paper serves as a solution to a current challenge and serves as a foundation for further research into the evolving landscape of remanufacturing optimization.

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Ergonomics of the TMS system in the context of the efficiency of the freight forwarder work – the example of TMS AndSoft

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Keywords: TMS system, automation, ergonomics, transport, management.
Abstract: The subject of consideration is to discuss key aspects related to the ergonomics and efficiency of IT systems, particularly in the context of Transport Management Systems (TMS). TMS supports the planning, control, analysis and optimization of flow processes, which translates into better technical resource management and cost reduction. Ergonomic design of IT systems aims to create intuitive and easy-to-use tools that minimize employee effort and reduce the number of mistakes made. This approach leads to increased work efficiency, which is crucial for companies, where process automation can significantly reduce the time needed to complete tasks and increase the efficiency of work. The article is based on the example of the TMS system from AndSoft and presents proposals for improvements of selected aspects of the system operation. The proposed improvements relate to the issue of planning and the creation of a unique feature allowing for cascading replenishment of resources, reducing the time needed to perform daily planning operations. In addition, it is proposed to synchronize two tabs “Orders” and “Availability resources” in order to find unplanned resources faster and assign them to specific transport ordersMoreover, an alert system was proposed to inform about errors made, which will allow for their quick detection and correction. In addition, a vehicle self-diagnosis system is proposed to monitor the technical condition of vehicles in real time. These innovative technological solutions contribute to increasing efficiency, reducing errors, and improving overall management of logistics elements.

1 Introduction

The development of information technologies and the constant pursuit of automation of both planning and operational processes creates predispositions for improvement and opens up opportunities for introducing improvements and innovative solutions. Today, logistics systems play a key role in the functioning of many companies, providing the basis for managing a wide range of business activities, including transport, warehousing, finance or human resources. The efficiency of the work performed is an extremely important element for companies in a constantly developing and competitive environment. Ergonomic process management translates into optimal use of time and better and more efficient performance of tasks, management, human flows, management of financial and work. Moreover, ergonomics of process management translates into optimal use of time and better and more effective performance of tasks and work. The focus on new information and telecommunication technologies contributes to the improvement of the quality of the services provided and the opportunity not only to attract new customers, business partners and markets, but also to the improvement of the results of the operations carried out [1]. The article presents an analysis of the ergonomics of AndSoft’s TMS system, examining how its features and functionality affect the efficiency of shippers’ work. The ergonomics of IT systems, although often underestimated, can effectively influence the productivity of people using the software. This paper presents an analysis of individual aspects of the TMS system from AndSoft, which, being the basic product, may not fully fit the needs of users. Despite the growing importance of TMS systems, much of the research conducted so far has focused mainly on technical aspects, often overlooking the influence of ergonomics on both operational efficiency and user satisfaction. Earlier studies frequently failed to address the specific needs of users, and the practical issues associated with using these systems.

The objective of the article is to present solutions that increase the efficiency of freight forwarders by improving the ergonomics of the TMS system. The study addresses the significant impact of ergonomic improvements on the productivity and well-being of dispatchers, underlining the relevance and necessity of investigating this research problem. The paper posed the following research questions: How does the automation of processes in the TMS system affect the time of execution of planning operations? What solutions can improve the ergonomics of the TMS system? What are the benefits of improved ergonomics in TMS systems? The above research questions have been formulated to focus attention on key aspects of the functioning of the TMS system and their impact on operational efficiency and user satisfaction. The answers to these questions will not only identify areas for improvement, but also propose concrete solutions that can bring tangible benefits to transport companies. The research is based on literature analysis and empirical methods. Literature analysis allows to identify existing solutions and best practices in the field of transport management and ergonomics of IT systems. Analysis of improvements will allow to check specific implementations in the TMS system, showing the effects of introducing different technological solutions.

Moreover, the article seeks to fill the existing research gap regarding TMS system functionality by offering an in-depth analysis of the ergonomics of AndSoft's TMS system. It examines how various features and functionalities of the system impact the efficiency of freight forwarders work and suggests targeted improvements to optimize ergonomics. The analysis covers several key areas, including process automation, its effect on planning operation times, and associated financial benefits, while also addressing potential implementation challenges. The article identifies essential areas that require enhancement and proposes innovative solutions that can provide significant advantages to transportation companies. Thanks to the analysis of the ergonomics it is possible to significantly improve shippers' daily operations, increase their efficiency and job satisfaction, and ultimately enhance service quality and transport process optimization. This comprehensive approach underscores the importance of ergonomics in maximizing the effectiveness of TMS systems and delivering practical benefits to the industry.

2 Literature review

2.1 Ergonomics of information systems

Ergonomics is a scientific discipline that deals with the analysis and optimization of people's working conditions, taking into account all factors affecting them [2]. Moreover, ergonomics is a multidisciplinary discipline dedicated to improving human physical and mental health to provide a safe, comfortable, and healthy environment, thereby enhancing efficiency. It involves the science of understanding and applying the interactions between humans and other elements of a system [3].

Researchers define ergonomics in various ways, according to W. B. Jastrzębowski "The name of Ergonomics, taken from the Greek words ergon (ergon) work and nomos (nomoz) law, principle, means the Science of Work, that is, about the use of forces and abilities given to man by the Creator" [4]. In the words of the author, ergonomics deals with research and optimization of working methods adapting them to the physical and mental capabilities of people. Ergonomics involves the study and optimization of working methods, adapting them to the physical and mental capabilities of individuals. It encompasses the application of principles from human biological sciences to optimize the fit between people and their work environment, leading to increased productivity and improved well-being [5].

Ergonomics in practical terms means adapting the various aspects of work to the capabilities of employees and improving the efficiency of the activities carried out. Although ergonomics is a humanistic field, placing the human being at the very centre of interest, the development of technology, research and other aspects of the field have broadened its scope of interest not only to the physical and biological aspects of adapting to changing working conditions, but also to the ergonomics of information systems, i.e. the time spent on tasks, the number of errors made and the adaptation of systems to user requirements [2].

Ergonomics is divided into two main approaches, namely corrective ergonomics and conceptual ergonomics. The first of these focuses on the analysis of prevailing working conditions in terms of matching their psychophysical predispositions to workers and users. Its main objective is to develop specific recommendations, improvements or modifications which will make an appropriate contribution to achieving harmonization of work and to reducing both physical and mental stress on man-machine systems, and to increasing the productivity and quality of work [6]. Conceptual ergonomics, on the other hand, begins with the planning or design of, for example, tools, machines, system software or workstations. Its aim is to establish in advance clearly defined interrelated functions between man and machine or system to reflect basic ergonomic requirements, with the least possible biological load on the person using the system or appliance, while maximising safety and productivity [6].

The main assumption of the ergonomics of information systems is therefore to create an environment in which there is compatibility between the system or software and the user. The system is a tool to be used by the user, so the person (the user) is the most important. According to M. Miłosz, "the ergonomics of the environment and computer tools (both software and hardware) determine the productivity of employees, as well as the costs of their activities" [2]. These aspects have a great impact on the functioning of the machine-man system. The first and most important goal when designing IT systems is to create an ergonomic interface. The physical and mental characteristics of users should be taken into account here. Properly designed interface is key to effective use of the software reducing stress and effort related to work, which consequently leads to a reduction in the number of potential errors, but also to improved work efficiency [6].

According to the aforementioned ergonomic aspects, it is crucial to adapt to the needs of the users. In the context of TMS (Transport Management System), it is important that it is designed with ease of use in mind. An aspect that greatly contributes to improving the ergonomics of IT systems is the interface. The user interface should first of all be clear, transparent and intuitive to use. Properly designed, it allows you to focus on important elements, making it easier to find them and perform individual tasks. In addition, it should clearly identify the main functions without the need for time-consuming search [2]. A home screen that is not designed as described often generates problems such as making mistakes and long-term searching for particular features, which consequently leads to user dissatisfaction and mental fatigue. Ensuring proper ergonomics of the IT system is able to increase operational efficiency, improve the well-being and efficiency of users. Important elements of the ergonomics of information systems include [2]:

- **Intuitive, easy to learn** (ease of use even for new users, minimization of training in operation and technical support),
- **memorability** (the system is easily memorized in operation, even after a long break),
- **legibility and transparency** (presents data in a structured, easy-to-find way),
- **adaptation to users' needs** (design taking into account users' expectations),
- **flexibility and personalization** (adaptability to individual preferences),
- **minimization of effort** (reduction of physical and mental loads),
- **maximization of automation** (reduction of repetitive, routine operations),
- **error rate** (minimization of error rate),
- **satisfaction** (maximization of work comfort).

The issue of ergonomics is linked to work efficiency, as well-designed IT systems can make a significant contribution to improving the efficiency and productivity of users. Work efficiency means that workers (users) achieve the best possible work outcomes as a result of their activities [8]. Work efficiency refers to the ability of employees to achieve specific goals with minimal expenditure of time, resources and energy. It can also be used to determine the efficiency and productivity of employees. In addition, this issue covers both the quality and quantity of the tasks performed. A high ratio means that the employee not only achieves satisfactory results, but also does so in a way that minimizes losses and maximizes benefits.

2.2 Features and Functions of TMS Systems

Today, in a highly competitive business environment, the efficient operation of a company's logistics system is a key aspect if a company wants to maintain profitability, minimize costs and meet the needs of its partners. Moreover, it can also be an indicator of the success of a company.

A logistics system encompasses a network of entities, individuals, operations, data, and resources that facilitate the movement of goods from suppliers to customers. It can be comprised of three primary networks or subsystems, such as procurement, production and distribution. More generally, a logistics system can be defined as a system comprising intentionally organized and integrated flows of materials and products, along with the corresponding information, within a given economic system [9]. The definition point out that these systems are created and implemented in companies for specific purposes, such as qualitative or financial. It is important that they operate smoothly, ensuring the free and fast flow of information, aiming at the optimal use of available resources, reducing costs and errors.

A TMS system, being a logistics system, can include key business issues and logistic processes, such as control strategies and tools used. Because these systems are ERP systems, they can fulfil a wide range of functions in enterprises [10]. Logistics researchers and specialists have a diverse approach to the concept of logistics systems, as they may depend on factors such as the sector of the economy, the nature of the activity and the functioning of the company.

The planning function, which is one of the most important, is responsible for the organisation of transport taking into account predefined transport conditions, such as volume, arrival and departure time, compatibility of the means of transport, trailers and so on. Ergonomic choice will depend on the amount of data and the transport plan by the dispatcher – locations of owned vehicles, transport tariffs, availability of drivers, loading methods, etc. [11].

Despite its name, the scope of activity of TMS systems is not limited only to transport management. The system can be expanded with specific modules, often depending on the software provider and user needs [12]. The following figure (Figure 1) shows examples of modules in TMS systems.

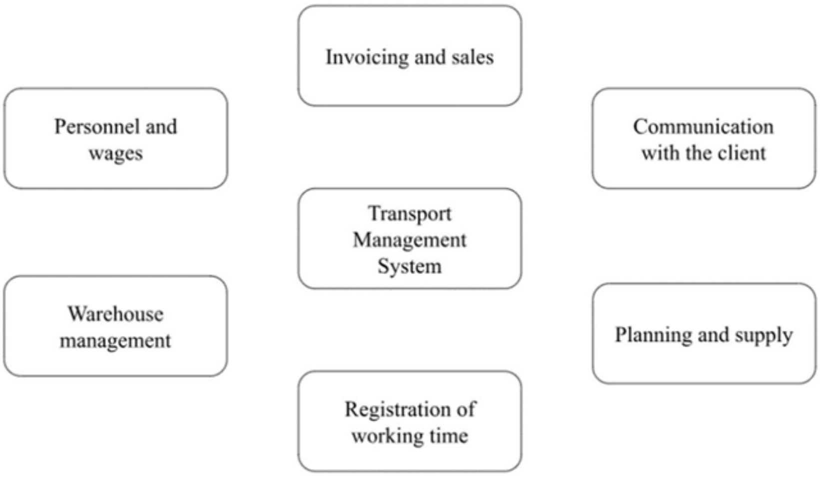

Figure 1 TMS system modules

The next stages of the analysis show the variety of functions that TMS systems perform. Particular attention should be paid to how technological solutions are able to affect the efficiency of shippers' work. Features such as fleet management, real-time route optimization, monitoring the status of vehicles, shipments, generating cyclic tasks for drivers significantly improve the efficiency of day-to-day operations and improve employee productivity. The functions of TMS systems in the literature are described in three main perspectives, namely in the functions of data processing, information functions and actual tasks assigned to the systems used. The first group includes [12]:

- **data recording -** storing information (integrated company data) and events in real time, limiting to a minimum manual data entry into the system,
- **data transformation -** actions performed on the collected information (calculation, sorting, indexing, combining and selecting data) - new information value,
- **storage, archiving -** storage of data in the system,
- **searching, filtering and presentation of data -** fluent information response to user queries and appropriate form of presentation.

Moving to information features that tell you what kind of information we may receive through the use of information technology and the levels of governance at which that information may be used. Stępniak C., Sobociński M. and Chluski A. distinguish six interrelated functions, which are presented in Table 1 [12].

Table 1 Information functions of TMS systems [12]

Lp.	Function	Description of action
1	Records of data	Collection of various data related to internal factors (data on ongoing processes, resources, etc.) and external factors (legal regulations, tax, insurance, etc.) for the needs of the organization.
2	Reporting and information	Regular preparation of datasets (according to specific criteria) reflecting the state of the organization and the processes taking place. Reports created for the needs of the company, e.g.: balance sheet, inventory, resource utilization rate or reports for tax and statistical offices.
3	Automatic analysis	Supports the performance of analytical tasks according to accepted methods to assess the state of the organization and compare results with historical, planned or industry data.
4	Automatic control	"Early warning" system when information is entered incorrectly or when parameters fall outside predefined ranges. Automatic control becomes particularly important in the process approach, as it automatically monitors the implementation of individual processes.
5	Planning	Generating sustainable plans for future periods, developing different scenarios for which information on the type and quantity of material inputs necessary to perform tasks is presented - used later in automatic control.
6	Supporting decision-making processes	Optimization of available decision options and selection of the most advantageous one based on adopted criteria.

The last area refers to the real tasks performed by the systems. They depend to a large extent on the activities undertaken in the company and the information needs generated on this basis. These relate to the scope of your business and may include activities such as fleet management, route planning, delivery scheduling, monitoring vehicle routes, creating workshop lists, inspections, servicing, selling services, creating invoices, orders, transport documentation, finance, human resources or customer communications. Depending on the needs of the transport company, the system will have to be flexible and adapted to the specifics of the transport industry, ensuring optimisation of logistics processes and efficient management of the fleet [12].

It is worth noting that nowadays, with such extensive functionality of systems and demand for information, it is advisable to use individual solutions that best meet the needs of a particular entity. You can buy ready-made products, but it is worth looking at them with a critical eye and consider implementing improvements. Adapting to the specific needs of the company will allow for a continuous process of improvement, change and acceleration of the work performed [13].

3 Characteristics of the TMS AndSoft system

TMS AndSoft is an ERP-class transport management system. It has many other functions, which depending on the demand (or department) can be used or not. It is necessary to pay attention to the functionality of its individual elements. The most important elements are those to which the user spends the most time in performing daily activities. First of all, it is worth paying attention to the initial interface of the program (Figure 2).

Figure 2 TMS - AndSoft interface

It is divided into several tabs, each of which is responsible for different areas of management. In addition, in each of them there are links to detailed tabs for performing daily work for the transport manager. As you can see, the initial screen is characterized by simplicity and minimalism, facilitating transparency even for new users. The aim of this action is to reduce unnecessary elements and facilitate navigation, which translates into the efficiency of using the system.

The first element of the system is the expansion of the "Master Files" tab (Figure 3). This tab is a database of all data about company resources, vehicles, trailers, drivers, customers, addresses, etc. It is a specific data source for all activities performed on other system tabs.

Figure 3 Master File tab

Another tab to pay attention to is the "Orders" tab (Figure 4). It allows you to check through various filters (1) generated orders in different time periods (2). To familiarize yourself with the order, simply enter it by pressing the button (3). This tab is used by shippers to find the orders they are handling during the given periods.

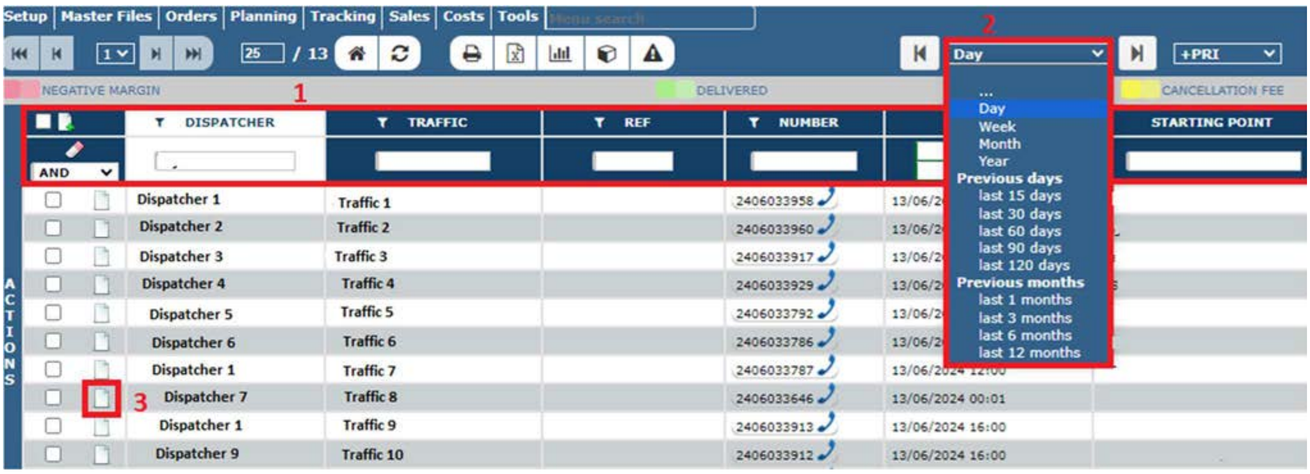

Figure 4 Orders tab

A transport order in the system is presented in the figure below (Figure 5). Entering the window contains a plan for the implementation of transport. It includes addresses, time frames and information about places of loading, unloading, and other stops (1). The "trash" and "scissors" icons allow you to remove or split waypoints, respectively. Another figure (Figure 6) shows how the system also allows to add references (2) and attachments from the drivers directly from their phones, which streamlines the documentation process (3). This ensures that all documents are securely stored in one place, eliminating the risk of losing them.

The figure (Figure 7) shows the process of planning a transport order. Orders are divided into segments, and their quantity depends on the specificity of the transport (number of points of loading, unloading, transhipment, driver change, etc.). Resource allocation is done by adding a corresponding resource to each segment (driver, vehicle, semi-trailer). In the present example, it is the vehicle 7057, the trailer t412 and the drivers BOES, BEOV and VEZA.

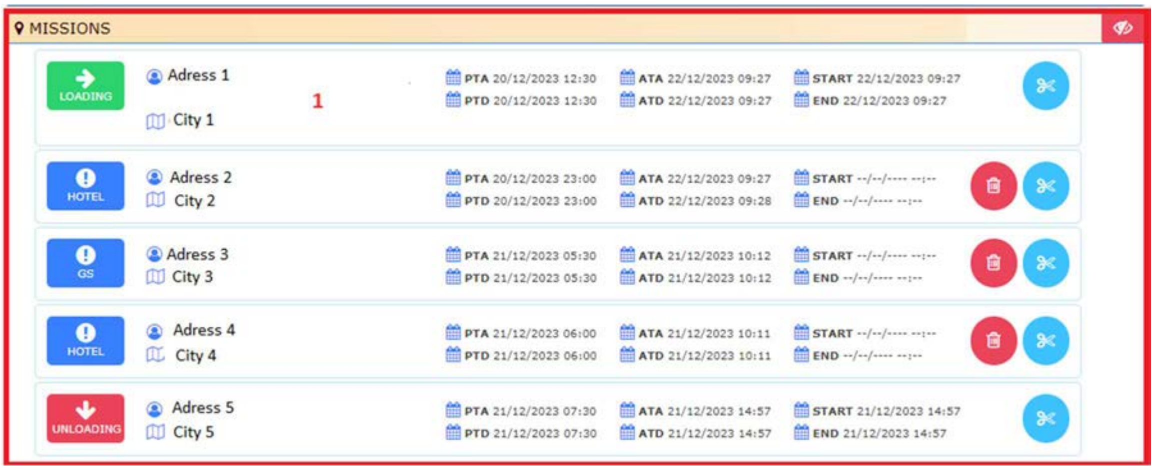

Figure 5 Transport order

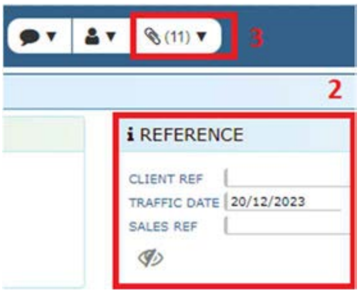

Figure 6 Logistic elements

Figure 7 Planning a transport order

An important element of the system is the “Planning - availability resources” tab (Figure 8), which is used to search for free, unplanned resources. It enables efficient management of company resources located in different locations without assigned tasks. By using this tab, it is possible to determine exactly where and when the vehicle, semi-trailer or driver will be available. However, the search for resources is still very time-consuming, due to the number of filters available and forcing the user to describe the needs in detail and then search and select the information received, resulting in complications and lengthy process. Additionally, manual data entry also carries the risk of frequent errors, which can affect the efficiency and accuracy of transport planning. Despite advanced tools and filtering options, inefficiency in finding the resources you need quickly is a challenge that affects overall performance.

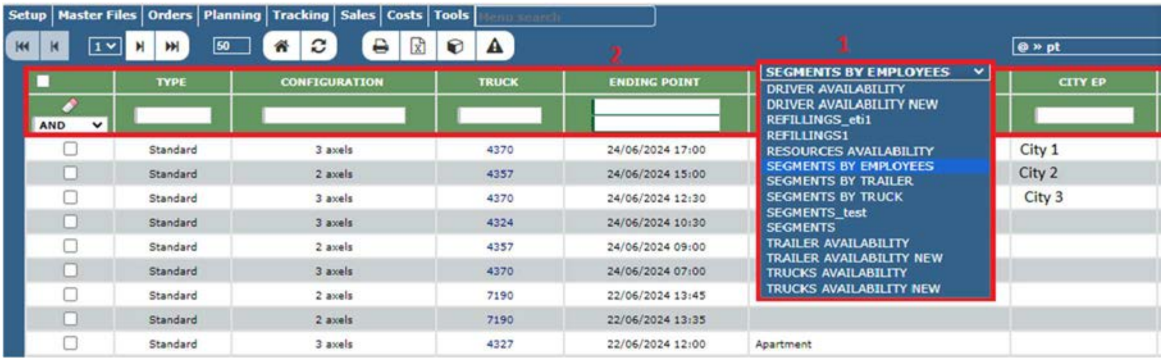

Figure 8 Planning - availability resources tab

Although, thanks to its extensive functionality, the TMS AndSoft system facilitates the work of shippers, it is possible to identify several problems and areas of potential improvement. Firstly, a noticeable problem here is the time-consuming and repeated replenishment of the same resources. Routes are divided into segments, due to ferry crossings, bridge crossings, loading, transhipment points, which generates additional segments that must be filled with the same information. This task is performed daily - drivers essentially perform the same tasks, however, they need to be sent instructions to carry out each day. The preparation of tasks falls under the responsibilities of dispatchers. Moreover, this requires spending time daily to manually enter and update information concerning the same resources, such as drivers, vehicles, and trailers. This repetitive and time-consuming activity not only burdens the employees but also increases the risk of making mistakes during data entry.

Secondly, the system lacks automatic control, which could lead to the possibility of duplication of resources. Lack of system alerts for potential resource duplication, can lead to planning, for example, one vehicle for two loads, causing confusion and unnecessary complications in work organization.

Another challenge is the time-consuming search for unplanned company resources, such as drivers, vehicles, and trailers, which can lead to a significant slowdown in logistical processes. Manual data entry also carries the risk of frequent errors, which can affect the efficiency and accuracy of transport planning.

The fourth problem is no control over the equipment of vehicles and trailers. The lack of effective control over the equipment of vehicles and trailers presents an additional obstacle, making it difficult to ensure the full technical readiness of the means of transport for order execution.

All these factors together impact the overall operational efficiency, increasing costs and the risk of delays in deliveries. An advantage of the TMS and ERP system is the ability to be flexible and fact that can adapt to mostly every need of the company. Using the system should be smooth and mistakes should be limited to minimum. In order to improve the transport management system, it is crucial to implement an alternative implementation that automates and optimizes these repetitive tasks, reducing work time and minimizing the risk of errors. Even minor modifications can significantly enhance efficiency and streamline workflows, making tasks both simpler and swifter to do. The right flow of information can help both to optimize the use of resources and to improve the coordination of flows in the supply chain, which can lead to improved ergonomics and reduced costs [14].

4 Methodology

The research methodology concerning the ergonomics of the TMS system is based on data and information sourced from a company currently using the TMS AndSoft system. These statistics provide comprehensive insights into various operational metrics and performance indicators relevant to the research, such as downtime of vehicle. By leveraging these data, we ensure that the analysis is grounded in the actual experiences of the organization. This approach allows for a examination of the impact of system enhancements on operational efficiency based on data collected from company's operational framework. Operational information, such as the times for completing specific tasks by dispatchers, was obtained from the company's internal reports. The time spent by dispatchers on performing selected tasks was measured, with the research sample consisting of 30 dispatchers at a similar level of proficiency in using the system, allowing for the acquisition of averaged results. The collected data enabled the determination of the average time required to complete transportation execution instructions. Times were measured twice, before and after the implementation of system changes. Based on the collected data, average times needed to complete transportation execution instructions were calculated. The measured times were compared with previous results to assess the improvement in ergonomics. Additionally, the research methodology included a literature review, which provided theoretical foundations on TMS systems, ergonomics, and process optimization in logistics. The financial data included average salaries for the position of international transport dispatcher in Poland, as well as average repair rates charged by truck service centers in the event of road breakdowns. This data was obtained from the company's documentation and market analyses.

It is important to emphasize that the research concerning the ergonomics of the TMS system originated from a bottom-up initiative proposed by employees using the system. Employees, based on their daily experiences and challenges related to system operation, identified specific areas requiring improvements. Their suggestions formed the basis for implementing changes aimed at increasing the efficiency and convenience of using the TMS system. This approach allowed for the direct consideration of practical aspects and the actual needs of users.

Additionally, the idea of introducing self-diagnosing vehicles was derived from the literature and existing practices in the transport field. Such solutions are already being used in various transport sectors, confirming their effectiveness in monitoring the technical condition of the fleet in real-time. Self-diagnosing vehicles enable the early detection of potential failures and the execution of necessary repairs before they affect the execution of orders. This allows companies to enhance the reliability of their transport operations and ensure a higher level of safety. Integrating this solution with the TMS system represents another step towards more advanced and automated logistics.

5 Increasing the efficiency of the forwarder by improving the ergonomics of the TMS system

This article mainly introduces a novelty study that explores a practical approach to the ergonomics of a TMS system, with analyses aimed at measuring the time and financial benefits resulting from better adapting the system to the specific nature of a dispatcher's work.

One of the main novelty is the introduction of automation during replenishment of resources. In the below figure (Figure 9.) we see a generated empty order that must be supplemented with resources and then sent to drivers. Proposition of time saving improvement is the ability to adjust the generated order with an earlier division, tasks and elements that will be performed permanently by one driver. For this purpose, an additional column with name: “instruction number” has been added, which shows the division of work created when completing instructions.

So far, resources are assigned individually to each segment and the dispatcher is forced to assign it to all of them manually. The use of automation processes during the execution of key planning processes and system operation can contribute to increased efficiency, ergonomic and improved security and quality of performed activities. The completion of the first segment would automatically complete the vehicle and the semi-trailer to the very end of the instructions and the driver to the point where his plan ends. Then, entering the next segment, it could be filled only by adding the initials of the next segment, which would automatically add information in every segment marked with the digit 2.


SEGMENTS

G.DIRECT	ASSIGN	LEG	ACTIONS	TRIP	SUBCO	TRUCK	DRIVER	TRAILER	DATE LO	DATE UN	MISSIONS	TP ID	INSTR.
		579807		GR2500395154					22/03/2025 22:00	22/03/2025 23:50	2		1
		579808		GR2500395156					22/03/2025 23:50	23/03/2025 02:17	2	16	2
		579811		GR2500395153	SCAND DK				23/03/2025 02:17	23/03/2025 03:17	2	16	2
		579812		GR2500395157					23/03/2025 03:17	23/03/2025 05:00	2	16	2
		579809		GR2500395158					23/03/2025 05:00	23/03/2025 06:00	3		3
		579810		GR2500395159					23/03/2025 06:00	23/03/2025 11:00	3		3

Figure 9 Empty order

Filling out each segment on the list takes 5 seconds, and the entire instruction consists of 8 segments. We need a total of 40 seconds to prepare everything completely. However, when automation comes into play along with assigning fixed tasks to a single driver, the whole process is reduced to three quick actions, each taking 5 seconds. In total, this takes only 15 seconds. As a result, we save 25 seconds on each such operation, which, in percentage terms, gives us as much as 62.5% less time spent on this task. Assuming that a dispatcher completes about 15 such instructions per day and the company employs over 30 dispatchers, we can estimate the specific benefits of automation.

Time benefits

1. Time saved per dispatcher per day:

$$15\ instructions \times 25\ seconds = 375\ seconds\ (or\ 6\ minutes\ and\ 15\ seconds)$$

2. Time saved by all dispatchers per day:

$$30\ dispatchers \times 6\ min\ and\ 15\ sec = 187\ min\ and\ 30\ sec\ (or\ 3\ hours, 7\ min\ and\ 30\ \text{sec})$$

3. Time saved by all dispatchers per month (assuming 20 working days):

$$3\ hours, 7\ minutes, and\ 30\ seconds \times 20\ days = 62\ hours\ and\ 30\ minutes$$

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4. Time saved by all dispatchers per year (assuming 240 working days):

$$62\ hours\ and\ 30\ minutes \times 12\ months = 750\ hours$$

Financial benefits

Assuming an average hourly wage for a dispatcher is 30 PLN (example rate):

1. Monthly savings:
$$62.5\ hours \times 30\ PLN = 1875\ PLN$$

2. Annual savings:
$$750\ hours \times 30\ PLN = 22{,}500\ PLN$$

In summary, automation and assigning fixed tasks to a single driver not only reduce the time required to prepare instructions but also provide financial benefits in terms of saved dispatcher work hours. Over the course of a year, the company can save up to 750 working hours, translating to 22,500 PLN.

For the second novelty improvement proposal is the implementation of an alert and notification system (Figure 10) in the event of a collision or duplication of assigned resources on the same transport days or an incorrect resource. This would inform users of a typing error. The system indicates an error by generating an alert in the form of an exclamation mark and changing the color of the corresponding fields to red, which would immediately draw attention to a potential problem. Visualization of errors is one of the elements of Lean Management and can contribute to minimizing errors and effectively highlighting errors causing an increase in the effectiveness of the management of operational processes.

Figure 10 Alert system

Applying this tool can bring the following benefits:

- prevention of mistakes - alert system can minimize human errors by providing notifications and reminders, enhancing accuracy and reliability in tasks,
- clear sign that resources should be checked - An alert system acts as an automated prompt for resource checks, ensuring that nothing is overlooked, and that all equipment is on correct place,
- improving the quality of offered services - By integrating alerts that prevent oversight and mistakes, the overall quality of services improves, leading to increased customer satisfaction and a stronger reputation for reliability,
- reducing the cost of potential errors caused on loading places.

Another proposal for the third novelty is to introduce a system of automatic assignment of resources to orders based on synchronization of the "Availability Resources" tab with the "Orders" tab. This operation would require the user to enter into the system the requirements for a specific order once (type of trailer and vehicle, load capacity and the level of utilization of the cargo space - choosing the most suitable type of semi-trailer). It would be the same information required for the previous proposition for the alerts. So, there will be two advantages in one. Due to this information, the system, using the available filters and data, could introduce proposals for automatic replenishment of free resources. This would only require the user to accept the system proposal or reject it and enter resources manually. Proposals would be available from the point of entering resources into the order and reduce the time of manually searching in the system for not used resources. Additionally, the system could also propose at first the trailer which his load capacity and the level of utilization of the cargo space will be the most suitable for the loading (Figure 11). As a result of use of this tool, the system would also take into account the fact of long-term vehicle downtime - the first priority would be vehicles or trailers that have not been used for a long time to make them active and used for work again. The same will be for the drivers - As for the indicator of work performed by drivers, this would also translate into the visualization of the number of hours worked - including kilometers traveled.

TRAILER	ENDING POINT	CITY EP	TYPE	SPEC	LOADING CAPACITY
T668	10.04.2024 16:30	GREVE	Standard	Box	66 EUR
T616	10.04.2024 15:00	GREVE	Standard	Box	66 EUR
T724	09.04.2024 23:00	GREVE	Standard	Box	66 EUR
T627	09.04.2024 16:30	GREVE	Standard	Box	66 EUR
T615	09.04.2024 16:15	GREVE	Standard	Box	66 EUR
T776	09.04.2024 16:00	GREVE	Standard	Box	66 EUR
T831	09.04.2024 13:00	GREVE	Standard	Box	66 EUR
T906	09.04.2024 09:00	GREVE	Standard	BOX	66 EUR
T899	09.04.2024 03:15	GREVE	Standard	BOX	66 EUR
T895	08.04.2024 16:15	GREVE	Standard	BOX TAPA	66 EUR
T775	08.04.2024 15:00	GREVE	Standard	Box	66 EUR

Figure 11 Example of proposition for trailer to use

Last proposition of novelty is development of a vehicle condition monitoring system. The on-board computer of the vehicle in real time would supervise and control the operation and condition of the vehicle - reading parameters (oil state, liquids, air leaks, tire pressure, air pressure, brake system or others). In the event of a breakdown (of course, one that is not required to be repaired immediately - necessary for safe continuation of the journey), the on-board computer would send a notification to the operator at the company with the relevant information along with a description of the fault and a preliminary scope of work required and a proposal for the repair [15].

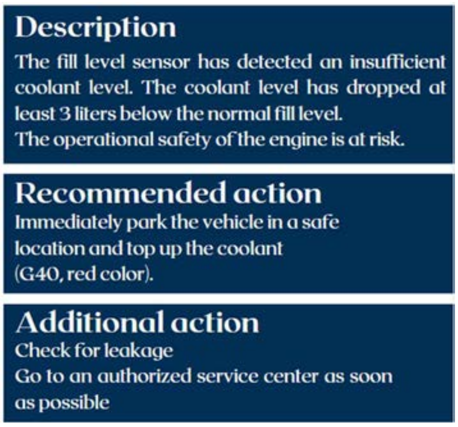

Figure 12 Example of notification

It can be an email or just a notification in the system (Figure 12). In addition, based on market prices and price lists available from servicing companies (ASO services) of individual repairs, the system would also show an approximate cost of repairs. Implementing such a system can contribute to:

- Avoidance of breakdowns and the ability to quickly repair the vehicle and execute the transport order on time,
- The time spent in the workshop and the associated downtime of the car are reduced to a minimum,
- Avoiding unnecessary workshop visits and repair costs,
- Information on the current state of wear of parts and fluids,
- Forecast of necessary maintenance activities.

In terms of numbers, the introduction of this system can bring the following benefits:

Reduce vehicle downtime

- Current Downtime: 10 days per vehicle per year
- Assuming a 50% reduction in downtime
- Downtime saved per vehicle: 5 days per year
- Fleet: 100 vehicles
- Total time saved: 500 days

Reduction of repair costs

- Cost of emergency repair in the field: 5000 PLN per vehicle
- Cost of planned repair: 3000 PLN per vehicle
- Annual breakdown rate: 10% (10 vehicles per year)
- Savings on repairs: 2000 PLN per vehicle
- Total savings: 2000 PLN x 100 vehicles = 200,000 PLN per year

Fuel optimization

- Average annual fuel consumption per vehicle: 50,000 liters
- Fuel savings: 5%
- Fuel savings per vehicle: 2,500 liters
- Fuel price: 5 PLN per liter
- Fuel savings per vehicle: PLN 12,500 per year
- Fleet: 100 vehicles
- Total fuel savings: PLN 12,500 x 100 vehicles = PLN 1,250,000 per year

Summary

- Downtime saved: 500 days per year
- Repair savings: 200,000 PLN per year

- Fuel savings: 1,250,000 PLN per year
- Total savings: 1,450,000 PLN per year

The implementation of these improvements will allow for better management of resources, significant improvements in ergonomics, greater user satisfaction, faster response to technical and operational problems and optimization of logistics processes, which in the long run will bring significant savings and improve the quality of services provided by companies.

The first three improvements – the alert system, synchronization of "orders" and "availability resources" tabs, and cascading instructions – are unlikely to involve additional costs, depending on the software vendor. These costs can already be covered by current operating fees and software vendor support. However, the implementation of these features will require implementation and programming of fixes, and then updating the system. The whole can last from 1 to 3 months.

On the other hand, implementing a self-diagnosis system, which monitors the technical condition of the fleet in real time, will be more demanding in terms of both cost and time. The estimated costs of implementing this solution may vary depending on the size of the fleet and the complexity of the system, but they can be assumed to be significant because all vehicles will have to be equipped with the appropriate equipment installed in the engines and programmed with the system. The time needed to fully implement such a system is usually several months, due to the need to integrate with existing infrastructure and train staff.

TMS systems are an excellent ready-made solution for transport and forwarding companies. In addition, much better results can be obtained by relatively low financial outlays on adapting the system to the individual needs of the company.

However, implementing the discussed system improvements also presents certain challenges that must be addressed. Understanding, identifying, and discussing these challenges is crucial for fully comprehending the process. The first potential issue is employee resistance to change. Users accustomed to existing procedures and systems may be skeptical about new solutions. These concerns may stem from fear of the unknown, a lack of understanding of the benefits, and a perceived threat to their work routines. This resistance can impact the success or failure of the changes. Researchers have long studied the causes of resistance and methods to manage it, many of them highlight that employee perceptions of fairness and reciprocity play crucial roles in the success of organizational changes [16]. Insights from these studies are particularly relevant in today's era of constant change, where managing employee resistance is crucial for organizational success. Effective communication of the purpose and benefits of new solutions is essential. It is important that employees have the opportunity to express their opinions and concerns about the proposed changes. This can be achieved by creating working groups responsible for testing and evaluating new system functionalities. A participatory approach allows for the early identification of potential issues and the implementation of necessary adjustments before the system is fully deployed [17].

Another challenge involves the costs associated with implementing system changes. Depending on the system provider, reprogramming and introducing new features may incur additional costs. If a company is already subscribing to a system, the introduction of new features might only be a one-time cost. Nevertheless, it is essential to conduct a detailed cost-benefit analysis to ensure that the investment yields the expected returns. Additionally, there are technical challenges related to integrating new functionalities with the existing system. Ensuring compatibility between new solutions and current systems is crucial to prevent issues with the flow or management of information and operational functionality. Furthermore, it is important to consider data security aspects. New systems must be protected against potential cybersecurity threats to safeguard sensitive information from unauthorized access [18].

The final aspect is change management. It is vital to involve all users, maintain transparent communication, and monitor progress to ensure that the implementation proceeds according to plan and achieves the intended goals. Incorporating these elements into the deployment strategy will minimize risk and maximize the benefits derived from ergonomic improvements in the TMS system, thus optimizing logistics and the flow or management of material, financial, and human flows [19].

Moreover, a huge advantage of the TMS and ERP system is the ability to be flexible and fact that can adapt to mostly every need of the company. Working on the system should be smooth and mistakes should be kept to a minimum. However, as it is known not everything is perfect, but according to the ethos of Kaizen, which inspires to constantly improve, it still can be a step closer to reach it.

Modern technologies such as robotics, advanced GPS systems and artificial intelligence enable transport companies to reduce costs, optimize processes and, most importantly, improve financial results. Over time, more and more companies are willing to implement innovative solutions to improve and streamline transport and delivery operations [20]. Flexibility, development and training of employees, and above all simplicity and ergonomics of systems, will be the key to improving decision-making and work processes in companies [21].

The flexibility of TMS systems and their ability to adapt to specific needs and changes enable continuous development, improvement, and progression toward perfection. Enhancements to logistics systems largely result in better ergonomics for day-to-day operations, higher service quality, and minimized errors. The ergonomics of the system, or its adaptation to the users' needs, plays a crucial role here [2]. The proposed improvements are only a part of the potential developments that can be integrated into the system, tailored to the specific requirements of all company departments. Enhancing the ergonomics of logistics systems not only improves daily operations but also enhances the quality of services offered and increases competitiveness. Innovative solutions facilitate better responses to market changes, more accurate data analysis, and more efficient resource management. The potential adoption of these technologies highlights the company's commitment to utilizing advanced logistics solutions to optimize operations. The ongoing evaluation of these proposals focuses on ensuring that any new implementation provides a tangible return on investment, both in terms of financial savings and operational improvements. By carefully considering the integration of these systems, the company aims to strengthen the technical elements of logistics, thereby supporting its strategic goals of enhanced efficiency, reduced costs, and improved service quality. This strategic approach underscores the importance of leveraging cutting-edge logistics solutions to maintain a competitive edge and drive continuous organizational growth.

6 Conclusion

TMS systems are of great importance, and ergonomics plays a crucial role in their functionality. Significant changes are possible thanks to continuous improvement and ongoing monitoring of technological innovations, such as the on-the-job sensors that provide valuable real-time vehicle status data. It is worth noting that two of the four proposed improvements have already been implemented in practice in the company.

Although the TMS system has been effectively utilized in various organizations for many years, it faces certain challenges, such as employee resistance to change, costs associated with implementing system changes, and change management issues.

In response to the identified issues, an initiative from employees has emerged to introduce several key modifications aimed at improving the functionality and ergonomics of the TMS system.

Empirical research conducted after implementing the proposed modifications revealed that these improvements significantly enhanced operational efficiency, increased planning accuracy, reduced order fulfillment time, and contributed to cost reductions.

The first implemented feature is the additional column for automatic replenishment of resources, which has significantly improved the flow of information and management processes. This column allows for the automatic entry of resources into orders, reducing the number of errors associated with manual data entry and saving a considerable amount of time. It automates the process of resource replenishment, enabling dispatchers to manage their tasks more efficiently. This automation not only enhances the efficiency of logistics operations but also increases the ergonomics of the TMS, making it more user-friendly and tailored to the needs of its users. Statistics and conducted studies indicate that a person responsible for completing orders and preparing instructions handles around 15 instructions daily, and there are approximately 30 such individuals in the company. The time needed to complete these tasks, after the introduction of the mentioned column, has been reduced from forty seconds to fifteen seconds, saving twenty-five seconds on each planning operation. A dispatcher completing 15 such instructions can save 6 minutes and 15 seconds per day, which translates to 62.5 hours per year per person. Considering all dispatchers, this amounts to a saving of 750 hours annually in completing instructions. This feature not only optimizes the flow of information and material management within the system but also significantly enhances the overall efficiency and effectiveness of the company's logistics operations.

The implementation of an alert and notification system is designed to address issues such as resource collisions, duplications on the same transport days, or the assignment of incorrect resources. This system immediately notifies users of potential errors by generating alerts, represented by an exclamation mark, and changing the color of the affected fields to red. By clearly and promptly highlighting errors, the system reduces the likelihood of mistakes and enhances the effectiveness of managing operational processes. This feature contributes to more efficient logistics management by ensuring that all resources are accurately and appropriately allocated, thereby improving the overall reliability and performance of the company's transport operations. In addition to minimizing planning errors, the alert system enhances the accuracy of logistics operations by providing real-time alerts to users and highlighting potential mistakes or discrepancies in the planning process. For instance, if an inconsistency is detected between the scheduled resources and the actual availability, the system immediately notifies the relevant personnel. This functionality ensures that errors are promptly addressed, thereby improving the overall quality and reliability of logistics processes. Moreover, the alert system enhances the flow of information within the organization, enabling swift decision-making and proactive management of logistics operations. This integrated approach to error management and real-time notifications helps streamline the allocation of resources and ensures a smooth flow of operations, ultimately contributing to the efficiency and effectiveness of the company's logistics management.

Two of the proposed enhancements remain under consideration and are subject to a cost-benefit analysis for potential implementation. These include the synchronization of the "orders" and "availability resources" tabs and the self-diagnosing vehicle system. The synchronization feature would allow for more efficient identification of unplanned resources, thereby optimizing resource utilization and streamlining the planning process.

This capability would enable a smoother integration of various logistics elements, improving the flow or management of available resources and information within the system. Although not yet implemented, this proposal is seen as a valuable addition that could further enhance the operational efficiency of the company.

IT systems are considered responsible for the efficient organization of data processing and information exchange within the system and with other external entities [22]. The company's TMS collects real-time data, which is then analyzed to provide valuable insights into fleet performance and operations. Measurability in the TMS plays a crucial role, as planning and operational aspects such as on-time delivery ratios and trailer and driver utilization can be accurately calculated and measured [23]. All these aspects contribute to improving the ergonomics of the entire logistics process [24]. The synchronization of the "orders" and "availability resources" tabs enables more efficient identification of free, unplanned company resources, significantly speeding up the planning process and, consequently, the fulfillment of orders. This also allows for more optimal use of resources that have been inactive for an extended period. Additionally, the proposed implementation of an alert system will minimize planning errors by clearly highlighting them, thus increasing the system's ergonomics.

Last one is the self-diagnosing vehicle system is one of the proposed innovative solution. This system would provide real-time diagnostic information about vehicles, significantly reducing downtime and maintenance costs by enabling preventive maintenance. Such technology is already in use in various fields, with some vehicle manufacturers, like Mercedes-Benz, offering similar solutions. For example, Mercedes-Benz's advanced diagnostics systems can monitor the health of vehicle components, predict maintenance needs, and alert drivers and fleet managers to potential issues before they result in costly breakdowns. This proactive approach not only improves the flow of information and material management within transport logistics but also enhances the overall reliability and efficiency of the fleet. Based on the conducted research, implementation of the system of a self-diagnosis system could reduce downtime by 50%, which in a company with 100 vehicles will save as much as 500 days of vehicle downtime. Moreover, the cost of scheduled repairs in the service compared to repairs of breakdowns on the road is able to save 2000 PLN per vehicle, which on a yearly scale and with 100 vehicles will amount to as much as 200 000 PLN savings. In addition, five percent optimisation of fuel consumption at assumed prices and average fuel consumption through ongoing servicing of fluids and components in vehicles can bring savings of 1,250,000 PLN per year for 100 vehicles. In the context of transport management, this could be one of the next breakthroughs. The implementation of these cutting-edge solutions allows efficient management of fleet servicing, minimising downtime, breakdowns and reducing repair costs [21].

The modified system is now operational in the company in a form that provides better integration with other tools, reduces the number of errors, positively impacts user well-being and work, and allows for more efficient management of resources and information.

In future research, we plan to conduct a comparative analysis of TMS systems with a focus on ergonomics. Additionally, we aim to undertake an in-depth modification of the TMS AndSoft system, accompanied by a comprehensive qualitative analysis of improvements in work efficiency.

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Human resource management in the logistics systems of modern companies

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Abstract: The key goal of the study is aimed at arguing the strategic aspects of human resource management in the logistics systems of modern companies. It has been determined that the effective functioning of modern companies cannot be imagined without human resources and a logistics system that ensures the life cycle of production of goods and services. The economic features of logistics systems of modern companies are substantiated. Structured resources of modern logistics systems of companies and practical recommendations for their rational use. A classification of human resources has been developed with arguments depending on their characteristics and type of implementation in the logistics system. The influence of the economic characteristics of the logistics activities of companies on the competitiveness and level of development of human resources has been demonstrated. To argue the strategic aspects of human resource management in the logistics systems of modern companies, multifactor correlation analysis tools are used based on data from global indices of logistics efficiency, human development, and competitiveness. The key trends in human resource management in logistics systems are identified, the correlation and interdependence of logistics, the effectiveness of human resource management and competitiveness are argued. Theoretical prerequisites for strategic human resource management in the logistics systems of modern companies have been developed and have their own value and importance. The obtained research results and generated scientific and practical recommendations can be applied when building strategies and long-term plans for the company's development in key areas: logistics, human resources and competitiveness.

1 Introduction

The functioning of modern companies is inextricably linked with the organization of efficient and stable logistics processes and supply chains, which are the key driving mechanism of the global economy. The purpose of the study is to determine the strategic aspects of human resource management in international modern companies based on the application of multifactor correlation analysis of global indices of logistics efficiency, human development and competitiveness. The logistics activities of modern companies are characterized by constant transformations and adaptive actions, which are associated with geopolitical uncertainty and lack of resources to fully perform key functions to achieve strategic business objectives. The intensity of growth of new technologies and innovations leads to the rethinking of existing ones and the improvement of business models and logistics systems of companies. Transformational processes of the global economy affect not only the business processes of companies' logistics systems, but also the processes of resource management, in particular human resources, which are a key link. It is important to note that in modern conditions, the need to scale a business, increase its efficiency, controllability transparency and optimize existing business processes cannot be imagined without the human resources of companies. Human resource management (HRM) is one of the strategic directions of modern companies since personnel and employees of companies are the most expensive resource that affects a number of competitive advantage of companies in the market.

The stability and continuity of supply chains today is one of the main strategic directions in the global dimension, since many economic processes depend on them, which have an impact on the overall socio-economic indicators of individual companies, industries and countries as a whole. Definitely, in recent years there have been intensive processes of gradual changes in approaches and methods for managing economic processes in the global economy, which are dictated by various factors of both a global and macroeconomic nature. In recent years, the issues of managing human resources of companies have become popular and relevant. Many world-class companies are interested in ensuring that human resources are adapted to changes, have the necessary competencies and qualifications in order to be able to solve non-standard complex problems of production, sales, service, logistics and support. Since, in contemporary conditions, to maintain a competitive position in the global market, technologies and their tools that replace human labour are not enough, personnel are definitely needed, which should be the key resource of companies. Considering what has been presented, it should be noted that human resource management in modern conditions should act as a conceptual element of strategic management, development and planning of the company's activities. The relevance of identifying a separate element of human resource management in contemporary strategies for the functioning of logistics systems of companies necessitates a detailed study and improvement of existing approaches. The demand for this direction leads to the argumentation of key theoretical aspects and the formation of scientific and methodological approaches to organizing effective human resource management in the logistics systems of contemporary companies.

1.1 Theoretical basis for the evolution of development approaches to human resource management

Conducting a contemporary business cannot be imagined without an effective strategy and an established mechanism for managing resources by companies, which together ensure the competitiveness, stability and long-term growth of the company. It is important to state that important in the strategy of each organization is personnel management, which represents a targeted impact that is necessary for organizing the activities of people in the production of goods and services, including the whole definition, organization execution, motivation, coordination and control [1]. In contemporary management theory and practice, it is worth highlighting the concepts that developed within the framework of the main new approaches to management - economic, organic and humanistic.

The formation of the presented approaches is due to the evolution of market relations. Definitely, all these approaches remain relevant and in demand when solving problems of personnel management to increase production efficiency. Based on this, it should be noted that the study of these approaches from the position of reflecting in them the essence of human resources, conceptual principles and management functions is necessary for the formation of a comprehensive understanding of the contemporary human resource management strategy of companies. It should be noted that within the framework of the economic approach, a strategy for managing human resources is distinguished, the guidelines for which are: technical, not management, training of employees; leadership; balance between power and responsibility; discipline and a clear hierarchy of subordination to key business tasks and company goals [2].

This approach is based on the centricity of the technical component rather than managerial training personnel in the company. Consequently, companies are considered as a mechanism and human resources as a certain element of this mechanism, which must function together. The basic principles of this concept include the following: ensuring the unity of the company's management in its goals and the desire for the company's development; compliance with managerial discipline and hierarchical management of subordination; fixing the required amount of control over personnel activities; compliance with the constructive separation of the headquarters and line structures of the organization; achieving a balance between power and responsibility; ensuring discipline in subordination and showing respect in accordance with corporate rules; achieving equivalence with the overall goals of the company. It is important to state that the concept of labor management is based on a bureaucratic organizational culture. Therefore, the manager in the process of his activities is guided by such stereotypes as: employees need management and control from managers; for employees, the incentive is, first, economic interest; the organizational structure must be designed to control the desire of workers and to the maximum extent should not neutralize the possible consequences of their unforeseen actions [3].

In the interorganizational approach to management, two concepts are distinguished: human resource management and personnel management. Specific qualities of an organic approach to personnel management are that in the management process the focus is on the selection of specialists, their training and career planning. The same or organizational approach is of great importance for new perspectives in personnel management, taking this type of management activity beyond the functions of work and compensation. The personnel function has gradually expanded by search and selection of specialists, career planning a significant figure for the company, feedback on the civilian management apparatus, and development of their qualifications. The argumentation of the role of human resources allowed to form a new vision of the company as a fundamental system. Analogies were used that determined a new view of the business environment. The first, based on the identification of the company with a human personality, determined the goals, needs, motives, maturity and decline or revival of the company. The second, taking the functioning of the human brain as a model for describing the organizational reality, allowed to look at the enterprise as components connected by lines of management, communication and monitoring. Recently, a humanistic approach to the management of the company's labor resources has been actively developing, considering people as a unique resource. The features of this approach are the focus on the organization of culture; the influence of the cultural context on personnel management [4]. Contemporary trends in digitalization of all industries have led to an acceleration of the life cycle of companies' goods and services and require them to quickly adapt and transform in order to appropriate new technologies and knowledge. In these conditions, the importance of creative teams or project groups increases sharply, which are created to solve non-standa rd problems. Hence, the formation of a team of workers by creating appropriate conditions for unification is of paramount importance workers in the production team and logistics systems of companies. Definitely, the transition to a humanistic approach to managing the labour potential of an enterprise does not mean a complete rejection of previous approaches, and their implementation in aggregate is possible, depending on the goals and objectives of the companies. It is necessary to note several main points that highlight its difference. Firstly, within the framework of this approach, attention is focused on the complication of the control object -person. A contemporary manager must unite not just individuals in the work collective, but the potentials of individuals. This task is necessary and at the same time difficult because it requires from the manager of mastering the latest technologies in personnel management. Secondly, taking into account the complex nature a person is determined by the dominance of socio-psychological methods of controlling his behaviour, since the latter is a phenomenon of socio-psychological origin. Thirdly, in addition to expanding the manager's functions, the importance of his role as an integrator of subordinates is growing. Fourthly, additional indicators the effectiveness of personnel management is becoming social indicators [5].

A significant addition to the above approaches to the evolution of personnel management may be taking into account changes in the role and functions of a manager, as well as changes in a person as an object of management Based on what has been presented, the authors, based on a scientific generalization, have formed a structuring of the evolution of the development of approaches to human resource management of companies, which is presented in Table 1.

Table 1 Structuring the evolution of development of approaches to human resource management of companies

APPROACHES	THE NATURE OF HUMAN LABOR	CONTROL OBJECT	MANAGEMENT METHODS
ECONOMIC APPROACH	Physical, Low Qualified	Human as a worker Power	Economic, Administrative
ORGANIZATIONAL APPROACH	Automated, needs a high qualifications	Human as a factor Production	Economic, administrative
HUMANISTIC APPROACH	Intellectual, Creative	Human as complex bio-psychosocial phenomenon	Comprehensive Application of all Management methods, Preference is given Sociopsychological Methods

Having stated the above, it should be noted that human resources management is a systematic organizational process reproduction and effective use of personnel to enable companies to take leading positions in competition [6-7]. Despite the considered evolution and development of the theory, there is an urgent need to determine the specifics of human resource management in the logistics systems of companies, which requires a more detailed study.

1.2 The theory of human resource management in logistics systems of companies

For long-term growth and ensuring the efficiency of contemporary logistics systems of companies, an integral part is the development of human resource management tactics, which are a key tool for companies to achieve competitiveness and scale their business. In the scientific literature, there are many studies and scientific approaches to analyze and focus on them, selecting the most relevant ones and those that are similar to the topic of research. The study of basic aspects of logistics and supply chain management is emphases in scientific approach [8]. A methodology for assessing human potential and training needs of employees in the pharmaceutical industry is propose. This approach emphasizes the importance and relevance of personnel development and its maximum adaptation to new technologies and tools, which is quite in demand and necessary in contemporary conditions. Definitely, the approach deserves attention, but does not reveal the main aspects of human resource management in the logistics systems of companies with the argumentation of key directions and trends in development, which requires improvement and further research. The argument for the need to ensure the efficiency of companies is present in study [9]. The use of strategic human resource management models to improve the efficiency of an organization is proposed. This approach is relevant and reveals the main aspects for increasing the efficiency of companies based on an integrated approach to data-driven management for long-term business success. Clearly, the approach reveals the main aspects of the organization of strategic human resource management, but does not reveal the features of their management in the logistics systems of companies, which requires improvement and development of this research.

The specific features of the functioning of marketing and logistics as a unified company management system in a pandemic are reveille in study [10]. This approach covers the main aspects of organizing the strategic management of a company, including marketing and logistics, taking into account many factors and uncertainty, which is relevant and in demand in contemporary conditions. The recommendations formed in the same way have their value and can be applied in practice, however, the specifics of human resource management in the logistics systems of companies are not disclosed, which requires further research. Historical aspects, the origin, essence and relationship of the key concepts of personnel management and human resource management are revealed in study [11]. This approach is basic in the theory of development of human resource management, the evolution and historical aspects of development are defined, but the features of management in the logistics systems of companies are not disclosed, which requires further addition and expansion of this research depending on the purpose and objectives of the study.

The argumentation of the features of the integration of logistics systems of developing countries into international logistics channels is considered in study [12]. The peculiarity and necessity of building a global logistics system in the world is highlighted with the argumentation of the main elements and tools for this. This approach is important when organizing an international or developing a company's global logistics strategy, but the role of human resources in this system and taking into account the specifics and need for implementation in the logistics system are not disclosed, which requires further research. An integrated approach to organizing logistics activities has been formed in study [13]. Key aspects of organizing logistics activities of companies are revealed, taking into account all influencing factors. This approach is fundamental for organizing the strategy of logistics activities of companies, but the essence of human resource management in this system is not revealed, which requires further research and expansion of the goals and objectives of the study. Having stated the above, it should be noted that in the scientific literature there are many studies and scientific approaches, however, there is no unified approach and methodology to the organization and management of human resources in logistics systems, which confirms the relevance and necessity of this research.

2 Methodology

2.1 Peer review process

The global intensity of development of new technologies and approaches to managing contemporary companies requires review and improvement of company management systems for their transformation and the need to ensure efficiency, optimal processes and profitability. Based on the use of scientific critical analysis and generalization, it has been proven that the effective functioning of contemporary companies cannot be imagined without human resources and a logistics system that ensures the life cycle of production of goods and services. Justified conceptual and economic features of logistics systems of contemporary companies. Structured resources of modern logistics systems of companies and developed practical recommendations for their rational use. Based on the classification, the author has developed a structuring of human resources depending on their characteristics and type of implementation in the logistics system. To achieve the key goal of the study in terms of the formation of aspects of human resource management of companies' logistics systems, the influence of the economic characteristics of the logistics activities of companies on the competitiveness and level of development of human resources is argued.

To substantiate the strategic aspects of human resource management in the logistics systems of contemporary companies, multifactor correlation analysis tools are used based on data from global indices of logistics efficiency, human development and competitiveness. Economic phenomena and processes of logistics activities of companies in current conditions depend on a large number of factors. As a rule, each factor separately does not determine the phenomenon being studied in its entirety. Only a complex of factors in their interrelation can give a more or less complete picture of the nature of the phenomenon being studied. To apply multivariate correlation analysis, several stages of data preparation were completed. On the first At the stage, factors that have an impact on the logistics systems of companies (indicators of effective logistics) are identified, and the most significant ones are selected for correlation analysis. At the second stage, initial information is collected and assessed, namely the structural indicators of the global logistics performance index, global competitiveness index and human development, necessary for correlation analysis. At the third stage, the nature is studied and the relationship between the factors and the effective indicator is modeled, that is, a mathematical equation is selected and justified that most accurately expresses the essence of the relationship being studied. At the fourth stage, the main indicators of correlation analysis are calculated. At the fifth stage, a statistical assessment of the results of correlation analysis and their practical application are given. To model the features of human resource management in the logistics systems of companies, it was determined that the effective indicator Y will be the global logistics efficiency index (LPI) , and the factor X1…XN signs that influence the effective indicator will be the following indicators: global indices of human development (HDI) and competitiveness (GCI), the totality of which is interconnected and has an impact on the strategy. Since the correlation relationship is fully manifested only in the mass of observations, the data sample size must be large. In this case, global indices are analyzed for all countries of the world as of 01.01.2024. The criterion for the homogeneity of information is the standard deviation and coefficient of variation, which are calculated for each factor and performance indicator. The standard deviation shows the absolute deviation of individual values from the arithmetic mean and is determined (1):

$$\partial = \sqrt{\frac{\Sigma(x-\grave{x})2}{n}} \quad (1)$$

The coefficient of variation characterizes the relative measure of deviation of individual values from the arithmetic mean (2):

$$V = \frac{\partial}{x} * 100\% \quad (2)$$

If the variation is more than 33%, then the information is heterogeneous and it is necessary to exclude atypical observations, that is, reduce the size of the data sample for structural indicators. When checking the compliance of the initial information with the law of normal distribution, the following condition is taken into account: the bulk of the information being studied for each indicator should be grouped around its average value, and objects with small or very large values should occur less frequently.

3 Result and discussion

The activities of the current business segment are inextricably linked with the organization of an effective development and operating strategy, which must take into account all aspects of the company's activities in order to ensure controllability, efficiency and profitability. It is important to note that the logistics system of a contemporary company is a separate planning and multifaceted area in the company's production activities, which includes planning operations with materials, their storage, transportation and much more. The main goal of this system is to deliver a product or service safely to a specific point within a specified period, spending a minimum of resources on this, ensuring transparency and efficiency of this process [14]. To substantiate the key aspects of human resource management in the logistics systems of contemporary companies, one should consider the conceptual goals and objectives of the logistics system, which is presented in Figure 1.

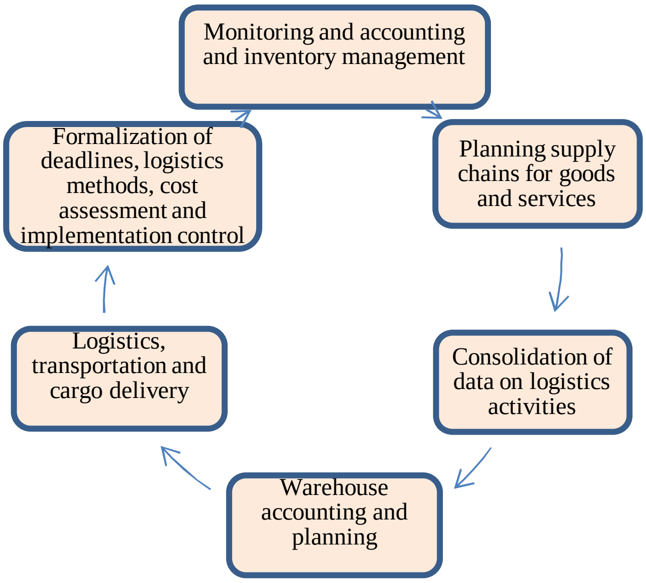

Figure 1 Conceptual goals and objectives of the logistics system of modern companies

Consequently, the logistics system of a contemporary company is aimed at ensuring the supply chain of the required products to the required place, at the specified time, at optimal costs, the required quality and quantity. The intensive development of contemporary technologies requires the acceleration of development and logistics processes, which is associated with the transformation of the global economy into a service economy with a key priority and focus on the consumer. In addition, factors influencing the intensive development of logistics systems of contemporary companies include the formation of global supply chains, a sharp reduction in the life cycle of products, the reorientation of traditional production to "made-to-order" production and mass customization, the structural complexity of goods and the rapid expansion of their diversity, the introduction new logistics technologies and logistics tools based on the implementation of information systems and logistics support technologies. All this is due to the ultimate need for contemporary companies to reduce the total cost and time spent associated with the movement of goods and services based on the implementation of innovations and technologies [15].

The priority condition for the effectiveness of logistics strategy and tactics is the organization of harmonious production and sales, the integration of logistics systems of companies in the main areas (production, supply, and distribution) in order to optimize resources when organizing a business and implementing a corporate strategy. The starting point for such integration is the continuous monitoring of demand dynamics, taking into account which the planned indicators of the component parts of the supply chain are developed and on the basis of which business scaling and the search for new segments and customers are carried out. It is known that a sign of production activity is actions aimed at satisfying human needs, often accompanied by the introduction of material changes in the resources used or their state in space and time. A feature of modern logistics is activity based on economic compromises and focused on customers. It is important to note that modern logistics systems of companies are complex to manage, as they include a number of components, elements and resources. Based on scientific generalization and structuring, the authors have formed conceptual features of the formation of resources of logistics systems of contemporary companies, which are present in Figure 2.

Figure 2 Conceptual features of the formation of resources of logistics systems of modern companies

Therefore, each type of resource in the logistics systems of contemporary companies should be considered in detail:

Material resources: represent the company's resources that are on the company's balance sheet and are presented in the form of investments, working capital and fixed capital. When organizing and building the business strategy of companies, supply chains are formed, which consist of links from other partner companies. With such a system of interactions, it is necessary to take into account the features of financial agreements that underlie partnership relations. An important fact is that when calculating costs in the supply chain, it is necessary to analyze the company's transaction costs. The presented explains the fact that the size of available assets determines the efficiency of the process of managing them [16].

Intangible resources of the logistics systems of modern companies represent unique information that has high managerial value for the company. The information mentioned is necessary for analysis and making management decisions and performing functions for organizing the supply chain, control and management of inventories, accounting, and others. It should be noted that intangible assets should be structured into key categories: reputation; strategic assets; own technologies. In modern conditions, reputation is included in the brand and trademark of companies that ensure the process of promotion and advertising of the company. Strategic assets are the advantages and strengths of companies that provide competitive positions in the market and characteristic elements of uniqueness and value. Proprietary technologies include copyrights and patents, which characterize the value and uniqueness of the company in contrast to competitors. Effective management of these assets provides a competitive advantage in the market and its scaling in accordance with the company's strategic priorities.

Human resources in the logistics systems of modern companies are characterized by the promising capabilities of the personnel who perform functional responsibilities when working in the company. The level of professionalism and the availability of special skills is determined by experience. For effective interaction and communication in companies, corporate ethics are formed; events and team building are held to consolidate the human resources of companies. The efficiency of human resources directly affects the efficiency of the company’s logistics system, which is relevant and necessary in modern conditions [17].

It should be stated that the modern human resource interaction with companies is characterized not as a multifaceted mechanism that fulfils specific goals and tasks, but as a reasonable and conscious individual who has goals, morals, aspirations and values. This type of interaction has a more global scope of interaction than the ordinary performance of certain tasks or tasks at the workplace. In any modern company, except for labour operations and functions that ensure the movement of material, financial, informational, service streams, human resources (company personnel) enter personal relationships, thereby creating a cultural environment, the social climate of the company. Human resources have a long-term nature of use and the possibility of development in the process of use.

Development of the company's human resource through training in in the process of their labour activity - a strategically important distinguishing feature of these resources appears in relation to all the others, which are present in Figure 2. Taking into account the above, it should be noted that the approach to human resource management is ensured by a balance between the flows (incoming and outgoing) of personnel so that the company's human resource potential evolves in accordance with the company's strategy. Optimization of personnel

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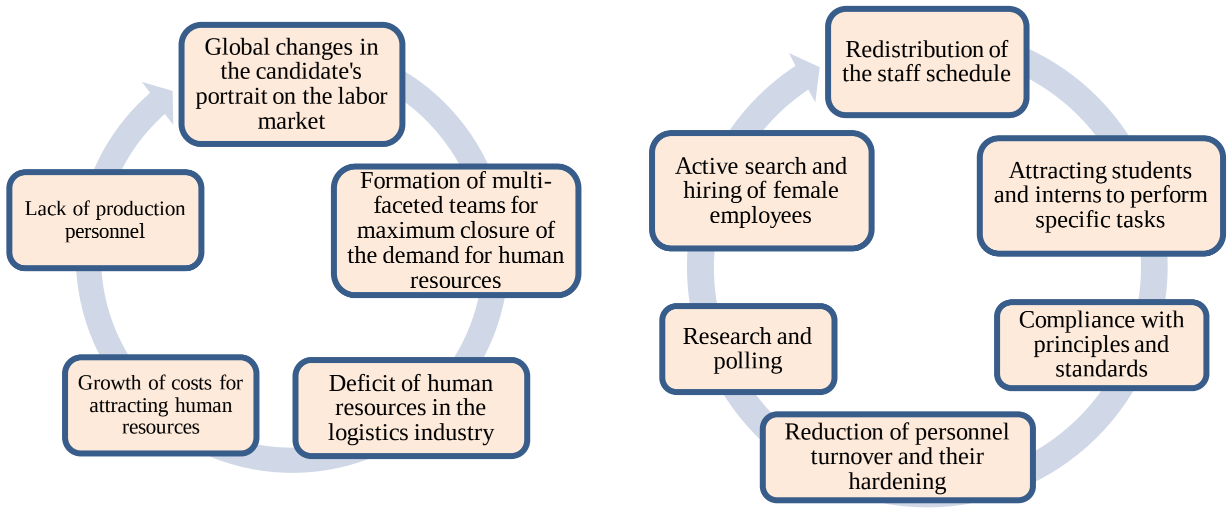
flows is a conceptual goal of human resource management in the logistics systems of companies. At the same time, when speaking about optimization, it is necessary to indicate the purpose of the movement of personnel flows, only this will ensure efficiency [18].

To substantiate the conceptual features of human resource management in the logistics systems of modern companies, the authors present the structure of human resource management in Table 2.

Table 2 Structure of human resources management in logistics systems of modern companies

OPTIMIZATION OF INCOMING STREAMS	OPTIMIZATION OF INTERNAL FLOWS		OPTIMIZATION OF OUTPUT STREAMS
	Training	Development	
ANALYSIS OF STAFFING	Labor organization	Training	Planning the release of personnel
PERSONNEL PLANNING	Motivation	Career planning	Dismissal of personnel
SELECTION AND INTERVIEW	Payment of labor	Social development	Analysis of staffing
RECEPTION OF PERSONNEL	Control		
ADAPTATION OF PERSONNEL	Personnel evaluations	Formation of the company's reputation and image	

Consequently, attention should be focused on the fact that in modern conditions of global transformations, there is a gradual change in the representations, approaches and methods of managing the economic processes of companies. In particular, relatively recently, the problems of managing human resources at the enterprise have acquired great importance. Economic entities are directly interested in forming labor teams that would have all the resources necessary to solve the complex problems of modern production. Based on this, the management of human resources is an integral part of the strategic development of the logistics system of the enterprise, as well as an integral part of the management process, in which the focus of attention is directed to the work of people. Through the management of human resources, management tries to achieve the main goals of the enterprise with the help of people. The activity of human resources management at the enterprise includes a number of actions on the part of the management, which together form the following cycle: personnel selection, certification and evaluation of personnel, motivation and remuneration, development and career growth. The activity of managing human resources in the logistics systems of companies is based on the principles and methods of a large number of sciences, including management theory and organization, labor law, labor economics, sociology, psychology, conflictology, ethics, political science, and a number of other sciences. In connection with this, it is not accidental that it is relevant and necessary to determine the main aspects of the management of human resources in the logistics systems of enterprises in modern conditions. Key trends and recommendations for optimization of human resource management in logistics systems are presented in Figure 3.



a) *Key trends of human resources management in logistics systems* b) *Recommendations for optimization of human resources management in logistics systems*

Figure 3 Key trends and recommendations for optimization of human resources management in logistics systems

The intensive growth of logistics activity in the world and its key place in global economics conceptually determined the importance and necessity of effective management of human resources. This is because the logistics industry occupies a leading position in the search for employees and the demand for new vacancies. A long search for candidates leads to a shortage of personnel and an increase in the closing time of vacancies, which entails an increase in the cost of attracting new employees, and has led to adjustments in human resource management strategies in the logistics systems of modern companies. Contemporary approaches to personnel retention are becoming central to human resource management not only in the logistics systems of companies, but also in general strategy. Modern companies must navigate the development trends of new approaches, management methods should not adapt to changes, but create them based on new technologies and innovations. Based on this, the authors conceptualized the key innovative and technological trends in human resource management in the logistics systems of companies, which are presented in Table 3.

Table 3 Key innovative and technological trends in human resource management in logistics companies in modern conditions

INNOVATION AND TECHNOLOGY TRENDS	INTRODUCTION AND BASIC PATTERNS OF HUMAN RESOURCE MANAGEMENT OF LOGISTICS SYSTEMS
IMPLEMENTATION OF ARTIFICIAL INTELLIGENCE OR MACHINE LEARNING IN HR PROCESSES	The implementation of artificial intelligence technologies has led to the emergence of various applications and programs for HR and recruiters that use artificial intelligence to perform certain tasks and find solutions. Artificial intelligence radically reduces the amount of time spent on certain tasks by up to 70% and optimizes human resource management processes, taking into account the basic directions of the company's logistics system.
HYBRID AND REMOTE WORKING MODE	The demand for office work is increasingly decreasing, and it is being replaced by remote and hybrid work modes. The advantages of this format are greater flexibility in work, increased productivity, savings in office maintenance costs, and greater diversity among employees. With the increasing use of technology and various communication channels, organizing remote work and building business processes in logistics and other industries has become much easier.
INCREASING REQUIREMENTS FOR HR	HR functions have become more strategic and focused on driving business growth. This is characterized by the fact that HR workers must set themselves all the highest goals and standards and, accordingly, demand appropriate knowledge, skills and qualities from their employees. Responsibility and ethics demands are also increasing, so expectations from HR are also changing and becoming more stringent. However, these qualities have many advantages in organizing the human resource management process, leading to increased productivity and productivity.
ENSURING EQUITY AND INCLUSION IN HUMAN RESOURCE MANAGEMENT	An inclusive workplace is a comfortable place with respect, personal space and opportunities for career growth. These principles allow many companies to create a favorable corporate culture in the workplace and attract more talent to the organization, while reducing the shortage of specialists and promoting the employer brand. Companies with high indicators of gender, ethnic and cultural diversity achieve higher profitability and enter new markets faster, and have at least 19% higher employee retention rates than companies that do not implement these principles.
AUTOMATION OF HUMAN RESOURCE MANAGEMENT PROCESSES	Automation and optimization of routine processes is gaining increasing relevance and demand in any field of company activity. Of course, this also applies to the human resource management industry, as evidenced by the multitude of automation tools and the popularity of entire HRM systems that increase efficiency and streamline human resource management.
DEVELOPMENT OF NEW LEADERSHIP METHODOLOGIES	Modern processes and their successful management require new leadership models that emphasize empathy, emotional intelligence and adaptability. One aspect of this trend is the development of new leadership models that better meet the needs of modern organizations. New models focus on employee intelligence, empathy and emotional intelligence as a key component of effective leadership. Companies will need leaders who can navigate complex and changing environments and manage and motivate remote workers.
Augmented reality and virtual reality technologies in initial and development programs	Augmented and virtual reality technologies are becoming increasingly popular in advanced and development programs. The development of AR and VR in the field of medical education by personnel will ensure the creation of immersive primary education, which will help students to begin training in a practical environment. Together with AR and VR, it is possible to create a realistic middle ground that will help healthcare workers focus on practical tasks and become more aware of working with new technologies, which can be improved and adapted in the future.
ANALYTICAL METRICS	As analytics and metrics become increasingly important in human resource management, companies are looking to monitor and measure their productivity in areas such as worker recruitment, employee turnover rates, and performance metrics. diversity. This trend is driven by the fact that most businesses have benefited from the infusion of data analytics into optimizing talent management strategies, increasing payroll and saving workers, and leading to business productivity.
CHATBOTS AND ONLINE ASSISTANTS	Chatbots and virtual assistants are computer programs that use artificial intelligence (AI) to imitate human intelligence, nutrition, and health care. The expansion of chatbots and virtual assistants in HR is a trend that is gaining popularity due to its potential to optimize communication and improve the visibility of employees.

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Companies introduce non-material bonuses and motivate employees to be interested in the company, which is confirmed by a friendly attitude towards each employee and an individual approach to his development and career growth. Undoubtedly, these measures are aimed at creating an attractive and comfortable working environment for the retention of qualified personnel in the conditions of fierce competition in the logistics industry, however, this will not ensure efficiency if it is not kept up with time. It is important for logistics companies to adapt to the changing labor market and the growing demands of employees. Optimizing hiring and personnel management processes can significantly increase work efficiency and staff satisfaction, and as a result, the logistics of companies [19].

It should be noted that the evolution of human resource management through the prism of organizing an effective logistics system of a company is relevant and necessary in today's conditions. Human resources are the most important and strategic resource of any company, without which it is impossible to imagine most business processes of logistics companies [20]. Taking into account the above, it is necessary to emphasize that the success of the logistics system of companies depends on a number of factors, including the optimality, transparency and controllability of human resource management processes that ensure the production process, build logistics supply chains and customer service. Based on this, the implementation of basic recommendations for human resource management in the logistics system of companies will not be enough, and it is necessary to analyze, study and implement trending approaches, tools and methods that are effective and ensure the achievement of strategic goals and objectives in short periods. Consequently, the development of technology provides new opportunities for business and workers, in particular in the field of human resource management of companies' logistics systems. Over the past few years, there have been intense trends towards the implementation of innovations and technologies in all sectors of the global economy, which leads to economic growth, transformation of existing management approaches and scaling of markets. Based on the presented, to argue the key aspects of human resource management in logistics systems, it is necessary to consider the key trends in the development of logistics activities in countries around the world, based on the global logistics efficiency index and its structural indicators, which are demonstrated in Figure 4.

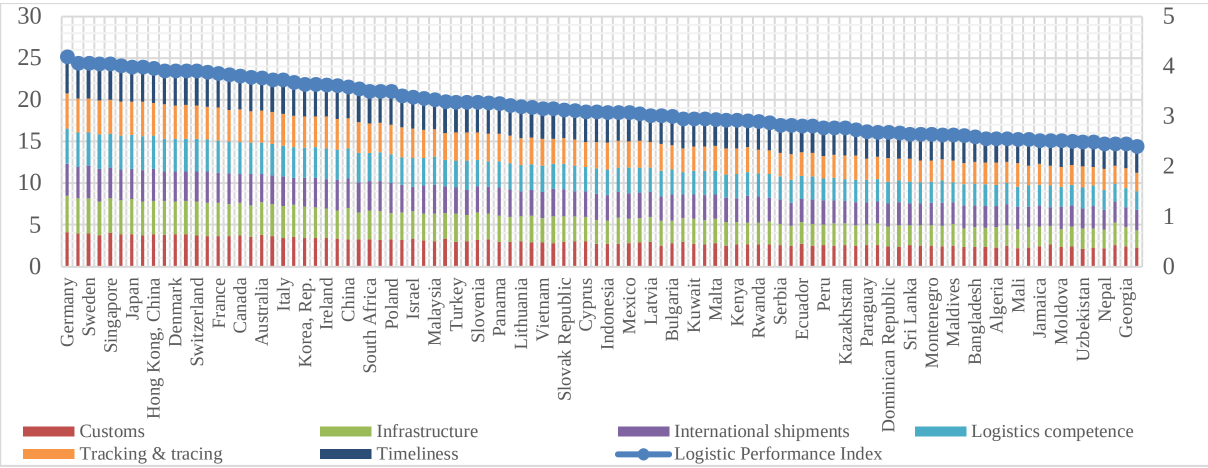

Figure 4 Trends in the development of logistics activities by country of the world based on the analysis of the global logistics efficiency index and its structural indicators as of 01.01.2024

The trends in the evolution of logistics activities are clearly presented in the light of the regional and structural indicators of the effectiveness of logistics. So, it is clear that the index shows what is taken for analysis a weighted average of a country's score on six key dimensions, indicating the relative ease and efficiency with which goods can be imported into and within the country. The trends in the evolution of logistics activities are clearly presented in the light of the regional and structural indicators of the effectiveness of logistics, so it is clear. That the index shows what is taken for analysis a weighted average of a country's score on six key dimensions, indicating the relative ease and efficiency with which goods can be imported into and within the country. The main tendencies and tendencies in the introduction of logistics activities in the world include:

- The increasing role of logistics in the global economy, which is ensured by the fact that efficient supply chains and logistics bring success to companies. This confirms the fact of the intensity of implementation of new technologies and innovations in logistics systems.
- Evolution of new technologies in logistics. The development of new technologies, including digital technologies, is fundamentally changing the logistics landscape. Automation, robotics, artificial intelligence and other technologies allow logistics companies to

increase the efficiency of their operations, improve service efficiency and reduce costs.

- Transformation of demand for logistics services. There will be a change in goods and services, and increasing competition will lead to a change in logistics services. Customers rely on logistics companies for more efficient, reliable and cost-effective services [20-21].

To argue the main aspects of human resource management in current logistics systems of companies, the need to implement multifactor correlation analysis tools is substantiated. Correlation analysis will determine whether there is a connection between the analysed indicators in one or two samples. If there is a connection, then an increase in one parameter leads to an increase (positive correlation) or a decrease (negative) of the other. Correlation analyses To carry out a multifactorial correlation study, an information base has been determined, which consists of a set of structural indicators of the effectiveness of logistics activities in the countries of the world (LPI), and to argue for its relationship with human resource management and the impact on the effectiveness of logistics management, it has been adopted on the basis of the human development index. Updating the relationship between human resource management and the need for it in the logistics systems of companies to ensure a high level of competition, an assessment of the influence of the global competition index was carried outs will determine whether the value of one indicator can be used to predict the possible value of another: differentiation coefficient of the human development index. Ccharacterizing the degree of difference in the socio-economic development of the analysed countries, regions within the country, social groups. Health index differentiation coefficient; education index differentiation coefficient; income index differentiation coefficient; mortality index differentiation coefficient as an indicator of differences in the health status of compared countries or regions; coefficient of differentiation of the level of vocational education, reflecting differences in the degree of enrolment in the second and third levels of education in the countries or regions under study [21-22].

However, in addition to the effectiveness of management and evolution of human resources, it is also important to have a management strategy, which should implement all these elements into a single system that will ensure the optimal logistics process of the company and increase its competitiveness in the global market. To argue the impact of human resource management in the logistics systems of the countries of the world, the impact of the global competitiveness index was assessed. The Global Competitiveness Index assesses the ability of countries to provide high levels of well-being for their citizens. Which primarily depends on how effectively the country uses the resources it has. At the same time, to maintain living standards in a free market, as a rule, a constant increase in labor productivity and the quality of goods/services is necessary. The dynamics of factor indicators (Global index of competitiveness; Index of human development), which have an impact on the management of human resources and logistics systems of companies, is presented in Figure 5.

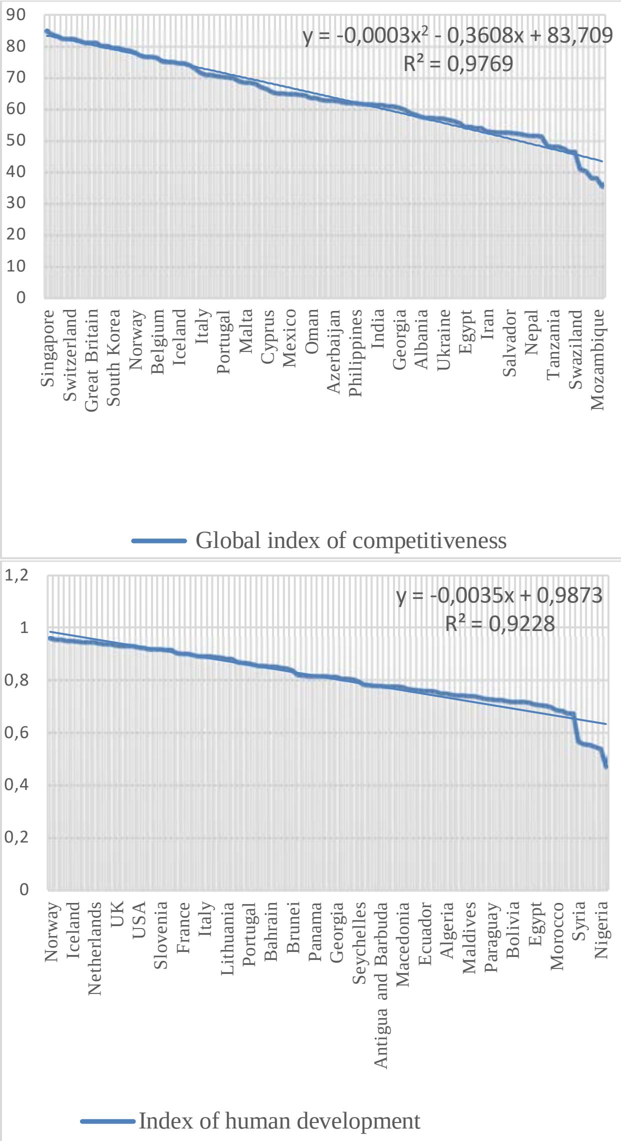

Figure 5 The dynamics of factor indicators (Global index of competitiveness; Index of human development), which have an impact on the management of human resources and logistics systems of companies

The dynamics of factor indicators (Global index of competitiveness; Index of human development) confirm the dependence and interconnection, which is visible on the basis of the statistical analysis. It should be noted that the global index of competitiveness of a country's economy largely depends on the quality of human resources. This quality of a resource is characterized by the level of both socio-economic development and the level of education, competence and learning ability. Undoubtedly, the development of human resources in modern companies and countries demonstrates the ability of the economy to ensure the efficiency of processes and phases of production of goods and services, which are reflected in the global competitiveness of the country. As has already been argued, the key and priority direction in ensuring the competitiveness of countries is logistics and the supply chain, which is directly related to human resources, the level of their development and adaptation to new challenges of the global economy. The logistics systems of modern companies are massively influenced by various factors and indicators at the global level, which have their role in the global economy. It should be noted that the effectiveness of modern business, as previously justified, cannot be imagined without resources, especially human resources, which are the main source of influence on companies in achieving their goals, objectives and plans. Based on this, within the framework of the argumentation of key aspects of human resource management in the logistics systems of companies, the use of multifactor correlation analysis is justified, during which performance indicators are determined (ABI and its structural indicators) and factor indicators that have their influence and interrelation (global competitiveness and human development index).

The main results of multivariate regression analysis of key aspects of human resources management in the logistics systems of countries around the world are presented in Table 3.

Table 3 The main results of multivariate regression analysis of key aspects of human resources management in the logistics systems of countries

PERFORMANCE INDICATORS Y_n	FACTORS OF INFLUENCE AND INTERRELATIONSHIPS X_n		RELIABILITY OF THE RELATIONSHIP R^2	PECULIARITIES OF INFLUENCE
	GLOBAL INDEX OF COMPETITIVENESS	INDEX OF HUMAN DEVELOPMENT		
LOGISTIC PERFORMANCE INDEX	0.045	0.578	0.923	Significant level of influence and dependence
CUSTOMS	0.521	0.345	0.045	Low level of influence and dependence
INFRASTRUCTURE	0.231	0.890	0.654	Moderate level of influence and dependence
INTERNATIONAL SHIPMENTS	0.692	0.987	0.041	Low level of influence and dependence
LOGISTICS COMPETENCE	0.745	0.924	0.035	Low level of influence and dependence
TRACKING & TRACING	0.045	0.567	0.893	Significant level of influence and dependence
TIMELINESS	0.045	0.001	0.941	Significant level of influence and dependence

The main results of a multifactor regression analysis of key aspects of human resources management in the logistics systems of countries around the world confirmed the previously formed theoretical assumptions and hypotheses. A strong level of interconnection and dependence is observed between logistics performance indicators: tracking logistics and delivery time, which are confirmed by determination coefficients. This is because all these indicators and business processes are based on human resources, which affects the efficiency and effectiveness of these areas. Changing one of the presented indicators will have a mirror effect on logistics performance indicators. Important dependencies and relationships are changes in the logistics infrastructure, which is directly related to the competitiveness of the company and can affect the process of organizing the process of managing human resources. Arguing the presented research results, it should be noted that human resource management in the logistics systems of companies should be a single whole, which is aimed at the implementation of business strategies, its growth and efficiency.

4 Conclusions

It is determined that strategic management of modern companies cannot be imagined without an effective system of human resources and logistics management, which complement each other and create a single system for achieving key business goals and objectives. It is substantiated that effective functioning of modern companies cannot be imagined without human resources and a logistics system that ensures the life cycle of production of goods and services. Theoretical prerequisites are formed that provide a justification for the economic features of logistics systems of modern companies. The resources of modern logistics systems of companies are structured, which made it possible to determine practical recommendations for their rational use. For the first time, a classification of human resources depending on their characteristics and type of implementation in the logistics system has been developed. Theoretical and scientific-practical aspects of determining the influence and relationship of the economic characteristics of the logistics activities of companies on the competitiveness and level of human resources development have been developed. The tools of multifactor correlation analysis are used, which made it possible to determine the strategic aspects of human resource management in the logistics systems of modern companies. The key trends in human resource management in logistics systems are identified, the relationship and interdependence of logistics, human resource management efficiency and competitiveness are substantiated. Formed theoretical prerequisites for strategic human resource management in logistics systems of modern companies, which have their own value and significance, are developed. The results of the study can be applied in building a strategy and long-term plans for the company's development in key areas: logistics, human resources and competitiveness.

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Performance analysis of production scheduling in Toyota simulation

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Keywords: production scheduling, simulated annealing, tabu search, Toyota production system, makespan optimization.
Abstract: This research analyzes production scheduling performance in the context of sustainable manufacturing using Toyota Production System (TPS) simulation. The primary focus of this study is to study scheduling performance based on the makespan value and job order for each method. To reduce makespan, two metaheuristic techniques are employed: the tabu search (TS) method and the simulated annealing (SA) method. This research fills the literature gap by exploring makespan optimization methods, combining computer simulation with metaheuristics, and considering TPS scheduling constraints. Data obtained from a miniature car simulation based on the Toyota Production System concept. The research method includes SA and TS implementation using Python and Visual Basic 6.0. The results show that SA and TS produce makespan 2.2-3.2% lower than the Initial Method. SA shows flexibility with different job sequences for each level of demand, while TS produces consistent sequences. The increase in makespan as demand increases is consistent across all methods (14.1-16.4%). In conclusion, SA and TS are effective optimization methods for production scheduling, with the selection depending on the preference for flexibility or consistency.

1 Introduction

Sustainable manufacturing has indeed emerged as a critical focus for many companies, driven by the need to reduce environmental impact and enhance cost efficiency. While Toyota Production Systems (TPS) have demonstrated effectiveness in boosting productivity and supporting eco-friendly practices, there remains a need for further enhancements in optimal production scheduling and cost reduction. Efficient production scheduling is paramount for sustainable manufacturing success, enabling companies to streamline operations, minimize lead times, and cut operational costs by optimizing resource allocation, setup time, and operation sequences [1]. Despite the lean manufacturing principles offered by TPS, challenges persist in implementing optimal scheduling in intricate and dynamic production settings, particularly within the realm of sustainable manufacturing [2].

Scheduling is a process for arranging existing resources to carry out production within a certain time period. This is because proper production scheduling can increase production efficiency, reduce production costs, and reduce idle time, as well as minimize work in process. The goal of production scheduling is to reduce the makespan, or the amount of time needed to finish every step of production. Makespan can be an indicator to assess production speed, the smaller the makespan value, the more effective the production activities carried out.

Various scheduling methods, such as the Simulated Annealing Algorithm and Tabu Search, play a crucial role in optimizing production systems [3]. The Simulated Annealing Algorithm, a statistical and probabilistic optimization method, generates diverse solutions with varying probabilities to find the expected solution, potentially leading to different makespan times in production scheduling [3]. Computer simulations, utilizing accurate models, are essential for analyzing and optimizing production systems, enabling companies to assess scheduling scenarios, identify bottlenecks, and test alternative strategies before implementation in real production settings, ultimately reducing costs and aiding in making informed decisions for sustainable production [3,4]. The Simulated Annealing algorithm produces random results to find the expected solution, so that if used in production scheduling this method will produce many solutions with several probabilities of course with different makespan time results.

Computer simulation has become an invaluable asset for analyzing and optimizing production systems, allowing companies to assess different scheduling scenarios, pinpoint bottlenecks, and experiment with alternative scheduling strategies in a virtual environment before implementation in real production settings [5-7]. By utilizing accurate simulation models, organizations can significantly reduce the costs associated with physical experimentation and make more informed decisions regarding sustainable production scheduling. This approach not only enhances operational efficiency but also aids in streamlining processes, increasing production throughput, and ultimately improving overall business competitiveness.

In the realm of production scheduling, simulated annealing and tabu search methods have been selected for calculating the makespan value, showcasing their effectiveness in tackling complex and NP-hard optimization problems [8]. These meta-heuristic techniques are excellent at solving problems with large solution spaces in a reasonable amount of computational time. Particularly in the context of Toyota Production Systems (TPS), where scheduling involves diverse constraints like setup time, resource availability, and operation sequences, simulated annealing and tabu search prove invaluable [8]. Simulated annealing employs a controlled cooling mechanism to evade local optima, while tabu search leverages tabu lists to prevent redundant searches, offering distinct perspectives for exploring solution spaces [8]. These techniques are essential for handling the complexities of production scheduling in TPS, guaranteeing effective and practical scheduling results.

By integrating simulated annealing and tabu search methods in scheduling optimization, this study leverages the strengths of each to enhance the chances of finding superior scheduling solutions, ultimately contributing to sustainable manufacturing efforts by minimizing makespan, which reduces energy and resource consumption while enhancing production efficiency [9]. The widespread use of simulated annealing and tabu search in prior research on production scheduling and optimization in manufacturing systems, including within the context of TPS, establishes a robust foundation for their application in this study [10]. This approach aligns with the broader trend in manufacturing towards energy efficiency and sustainability, highlighting the potential for these methods to provide more optimal scheduling solutions and support sustainable production practices [9,10].

This research aims to analyze scheduling performance in the context of sustainable manufacturing using Toyota Production System simulations. By optimizing production scheduling based on makespan value. It is hoped that this research will provide valuable insights for manufacturing companies in their efforts to achieve greater operational efficiency and reduce environmental impact, as well as support sustainable manufacturing practices.

2 Literature review

2.1 *Scheduling*

Production scheduling plays a crucial role in manufacturing operations, aiding in achieving efficiencies, cost reduction, and supporting sustainable manufacturing practices. Various studies highlight the significance of optimal production scheduling in different industries. Hubert and Bleidorn emphasize the benefits of deep reinforcement learning (DRL) for optimized scheduling in the chemical industry [11], Lan and Chen [4] concentrate on the use of AI technology in intelligent manufacturing cells for unitary production scheduling. Additionally, Udayakumar et al. stress the importance of green technology efforts in reducing carbon emissions and setup costs through optimal production scheduling[12]. Torres underscores the complexity of decision-making processes in aquaculture and the need for decision support methods to enhance operational efficiency through production scheduling [13]. These studies collectively demonstrate the critical role of optimal production scheduling in enhancing production flow, reducing waste, and increasing productivity, aligning with the principles of Toyota Production Systems (TPS).

In industrial operations, production scheduling is critical, especially in lean systems like the Toyota Production Systems (TPS), where it is necessary to achieve efficiency, cut costs, and promote sustainability [14,15]. Previous research emphasizes the significance of effective production scheduling in lean sustainability, highlighting its role in waste reduction and resource efficiency [14,8]. Integrating environmental and economic aspects in optimization processes is key to sustainable production scheduling, as seen in multi-objective models considering energy consumption, production cost, and cycle time within TPS contexts [13,12]. Metaheuristic methods like genetic algorithms and local search have been employed to enhance scheduling performance and minimize energy consumption and costs in lean production systems [8,15]. Additionally, computer simulations have proven valuable in analyzing and optimizing production systems, providing insights into the environmental and economic impacts of continuous production scheduling in TPS environments [8,13,15].

2.2 *Toyota Production System (TPS)*

Toyota Motor Corporation created the well-known lean manufacturing approach known as the Toyota Production System (TPS), incorporating principles such as just-in-time (JIT) and jidoka, focusing on timely production and intelligent automation to prevent defects [16]. TPS also includes continuous improvement (kaizen), process standardization, and waste elimination, leading to increased productivity, cost reduction, and enhanced product quality [16]. Recent research by Nahmens and Ikuma highlights TPS's role in lean sustainability by reducing waste and enhancing resource efficiency. Chiarini and Vagnoni emphasize the significance of TPS in supporting sustainable manufacturing practices, showcasing its effectiveness in achieving operational excellence and sustainable manufacturing goals.

Several studies have indeed integrated sustainability aspects into production scheduling optimization within the context of the Toyota Production System (TPS). A multi-objective optimization model considering energy consumption, production costs, and production cycle time in Toyota's production system . [17] analyzed the impact of sustainable production scheduling on environmental and economic performance in TPS, focusing on carbon emissions and resource consumption. Hybrid optimization method for continuous production scheduling is conducted through agent-based simulation on Toyota production system. Additionally, [1] provided a comprehensive review of simulation usage in sustainable manufacturing, including TPS applications. These studies collectively highlight the importance of incorporating sustainability considerations into production scheduling optimization within the TPS framework, emphasizing the need for environmentally and economically efficient practices.

2.3 Simulated annealing and tabu search

Simulated annealing is a metaheuristic method widely applied in solving complex production scheduling optimization problems, inspired by metallurgical annealing processes [18]. This technique efficiently explores solution spaces to identify optimal or near-optimal schedules by iteratively modifying solutions and accepting new ones based on goal function improvement or with a probability to avoid local optima. Additionally, simulated annealing with adaptive cooling schedules has been proposed to enhance convergence speed and performance in optimization problems, offering a theoretically sound approach with variational approximations of Boltzmann distributions. Furthermore, it has been demonstrated that simulated annealing, when combined with suitable cooling schedules, can compute precise constant-factor approximations for the minimal spanning tree issue in polynomial time, demonstrating its adaptability and efficiency in a range of optimization applications[19].

In the realm of sustainable production scheduling, simulated annealing has been extensively utilized to enhance scheduling efficiency by considering factors like energy consumption, carbon emissions, and production costs. In a multi-objective optimization model for continuous production scheduling in lean production systems, [12] used simulated annealing. [4] focused on energy and carbon emissions inside Toyota Production Systems and used simulated annealing to optimize production scheduling. Additionally, [8] suggested a hybrid optimization strategy for continuous production schedule optimization in Toyota Production Systems that combines genetic algorithms and simulated annealing. Despite its effectiveness, simulated annealing can suffer from drawbacks such as prolonged computational time and parameter selection challenges, leading researchers to explore variations and hybrids with other methods to enhance its performance [20].

Tabu Search is a powerful metaheuristic approach extensively utilized for tackling complex and NP-hard production scheduling optimization problems. Inspired by human search behavior, it employs adaptive memory to prevent revisiting previously explored solutions, enhancing efficiency [21,22]. The search process in Tabu Search begins from an initial solution and iterates through neighboring solutions by making adjustments; if a neighboring solution proves superior, it replaces the current one, facilitating continuous improvement [21]. To circumvent local optima traps, Tabu Search employs a tabu list that records visited solutions, ensuring that the algorithm explores diverse solution spaces and avoids stagnation [21,23]. This strategic use of memory and solution tracking enables Tabu Search to navigate complex problem landscapes effectively, making it a valuable tool for optimization tasks in various domains [22].

In the realm of sustainable production scheduling, Tabu Search has been a valuable tool for optimizing scheduling performance while considering critical factors such as energy consumption, carbon emissions, and production costs. Research studies like [8] focus on utilizing Tabu Search within a multi-objective optimization framework to enhance sustainable production scheduling in lean manufacturing systems, emphasizing the reduction of carbon emissions and energy consumption. Additionally, works such as [2] demonstrate the effectiveness of Tabu Search in hybrid optimization methods, combining it with genetic algorithms for continuous production scheduling optimization in systems like Toyota Production Systems. These studies underscore the versatility and efficiency of Tabu Search in addressing the complexities of sustainable production scheduling across various manufacturing environments

By investigating sustainable production scheduling optimization within the framework of the Toyota Production System (TPS), this study seeks to close a gap in the literature. The research's position is shown in Table 1.

Table 1 Research gap

No.	Research Gap	References
1	Integration of sustainability aspects in TPS production scheduling optimization, specifically focusing on simultaneous minimization of production costs, energy consumption, and greenhouse gas emissions.	[2,12,23]
2	Exploration of scheduling optimization methods to minimize production costs in TPS simulation, considering the influence of employee and tool selection on the scheduling process.	[15,24]
3	Integration of computer simulation with metaheuristic methods (such as simulated annealing and tabu search) to optimize continuous production scheduling in Total Productive Systems (TPS).	[25,26]
4	Integration between classical scheduling theory and practical scheduling applications in	[27,28]

	TPS, considering constraints such as setup time, resource availability, and operation sequence.	
5	Practical validation and implementation of optimized production scheduling solutions in real TPS environments, including verification using discrete event simulation (DES).	[29,30]

3 Methodology

3.1 Data collection

The goal of this research is to create a production process simulation at lean manufacturing laboratory, which is part of the department of industrial engineering, Hasanuddin University. The research data used in this research is divided into 2 data, namely primary data, which is data obtained directly while in the field. The data collected is in the form of cycle time for each work station, obtained from time measurements, rating factors obtained directly while working, allowances obtained directly when workers do work, number of processes and the number of machines and equipment used. , Sequence of vehicle assembly work. Secondary data is data obtained without making direct measurements or observations. Secondary data for this research is product type and specifications, data on the number of consumer requests, and a simulation master plan.

The population and sample in research are important aspects taken to draw general conclusions. The population and sample in this study are as follows. A population is an approximation made up of items with specific attributes chosen by researchers for analysis and inference. Based on the population definition, the population of this study is the observation time of the production process of the 6 specimens tested. The sample is part of the number and characteristics of the population. The sample used in this research was random sampling. Random sampling was used to reduce data bias in this research.

3.2 Test materials and instruments

The test materials used in this research were 5 miniature cars, namely, miniature P/U cars, D-Cab, MPV, Excavator and Truck Mixer. Figure 1 displays the types of materials used in the research.

Figure 1 Test materials

A number of data gathering techniques were employed in this study, including a review of the literature, direct data collection from the Lean Manufacturing Laboratory during the simulation process, and observation, and carrying out simulation tests related to the vehicle assembly process in the Lean Manufacturing Laboratory.

The research method used in this research includes statistical analysis to assist researchers in processing initial data. Researchers also use the Simulated Annealing and Tabu Search algorithms as methods for determining new scheduling solutions. The Simulated Annealing algorithm itself uses Python as a tool to complete the algorithm. Meanwhile, the Tabu Search algorithm uses Visual Basic 6.0 (VB6) software.

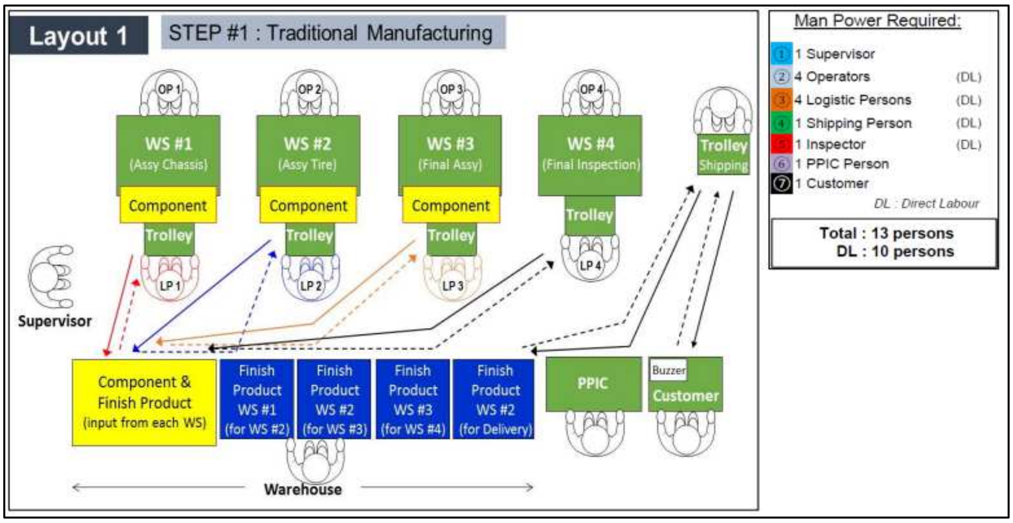

Figure 2 TPS simulation scenario [31]

The simulation, depicted in Figure 2, will take place in the setting of a business that employs a conventional production system and still needs a warehouse to store raw materials, semi-finished products, and finished goods that are prepared for shipment to customers. The following is the simulation scenario that will be carried out:

- The alarm will sound every 1.5 minutes.
- The customer gives the order to the PPIC (Production Planning and Inventory Control) after the first alarm sounds.
- The PPIC gives the production order sheet to the production supervisor.
- The supervisor gives production instructions to each Work Station and monitors during the simulation.
- The Work Station Operator works according to the instructions after the second alarm sounds, requests an empty box for finished goods, and asks the supply operator if the goods are finished. The operator can process goods out of sequence.
- The supply operator goes around to the designated Work Station to provide empty boxes and send finished goods to the warehouse, as well as supply components from the warehouse.
- The shipping operator prepares the shipment of goods by picking goods from the warehouse according to the PPIC process if the goods are available. The first shipment is made after the sixth alarm sounds, and the preparation for the second shipment is made when the seventh alarm sounds, with the shipment after the eleventh alarm sounds.
- The Work Station #4 operator (inspector) checks the quality of the goods and records the results on the quality check sheet. If NG (Not Good) goods are found, place them in the NG goods area.
- The warehouse operator prepares materials to fill the reduced or out of stock, provides empty boxes for finished goods, and places finished goods from each Work Station according to their addresses.
- Customers check the items that have been delivered using the delivery confirmation sheet.
- The simulation stops when the twelfth alarm sounds, and PPIC records the stock on the evaluation sheet.
- Have a discussion about the simulation based on the evaluation sheet and observation points.

The point that will be seen during the simulation is the makespan value based on demand variations consisting of three demand variations with a job sequence consisting of six jobs.

4 Results and discussion

In this research, a comparison of three production scheduling methods was carried out: Initial Method, Simulated Annealing and Tabu Search in the context of optimizing production schedules for six types of vehicles at four workstations with three different demand scenarios. Table 2 shows demand data for six different vehicle types in three different demand scenarios. Vehicle Types in Table 2 includes six different vehicle types, each coded J1 to J6. J1: Pick Up J2: MPV (Multi-Purpose Vehicle) J3: Double Cabin J4: Concrete Mixer J5: Excavator J6: Roller Cylinder Truck. The Demand Scenario consists of three different demand scenarios, namely Demand 1, Demand 2, and Demand 3. Each scenario shows an increase in demand from the previous one. Demand for each type of vehicle consistently increases by five units for each demand. This increase pattern was consistent for all types of vehicles, indicating uniform demand growth. Vehicles with the highest demand: Pick Up (J1) and Concrete Mixer (J4), ranging from 35 units in Demand 1 to 45 units in Demand 3. Vehicles with the lowest demand: Double Cabin (J3) and Roller Cylinder Trucks (J6), starting from 27 units in Demand 1 to 37 units in Demand 3. This consistent increase in demand indicates the need to increase production capacity gradually. The difference in demand between vehicle types indicates the need for different resource allocation for each production line.

Table 2 Demand data

Job	Type	Demand 1	Demand 2	Demand 3
J1	Pick Up	35	40	45
J2	Mpv	31	36	41
J3	Double Cabin	27	32	37
J4	Mixer Beton	35	40	45
J5	Excavator	31	36	41
J6	Truck Silinder Roller	27	32	37

4.1 Initial method

Table 3 displays information about variations in makespan and job sequence for three different demand scenarios using the initial method.

Table 3 Makespan and job sequence initial method

Demand Variations	Makespan (minute)	Job Sequence
Demand 1	588.54	J1 - J2 - J3 - J4 - J5 - J6
Demand 2	681.38	J1 - J2 - J3 - J4 - J5 - J6
Demand 3	774.22	J1 - J2 - J3 - J4 - J5 - J6

Table 3 provides an illustration of how total completion time (makespan) changes as demand increases, while job order remains constant. There was a significant and consistent increase in makespan along with increasing demand. From Demand 1 to Demand 2, makespan increases by 92.84 time units (15.8% increase). From Demand 2 to Demand 3, makespan also increases by 92.84 time units (13.6% increase). This linear increase in makespan shows a proportional relationship between increasing demand and total production time. For all three demand levels, the job order displayed is the same: J1- J2- J3- J4- J5- J6. The consistency of this job sequence shows that the initial method uses a static or fixed approach, not considering changes in demand levels. This order may be based on fixed priorities or simple scheduling rules such as First Come First Served (FCFS). This static scheduling approach may be simple to implement, but may not be optimal for all levels of demand. A significant increase in makespan indicates that production capacity needs to be increased proportionally to the increase in demand. Maintaining the same job sequence despite increasing demand may not optimize resource usage or minimize completion time. This method does not consider the possibility of different bottlenecks at different demand levels, which could be a reason for job sequence changes.

4.2 Simulated Annealing (SA) method

In this research, the Simulated Annealing Algorithm is used as a reliable computational solution to overcome production scheduling problems. The implementation of this algorithm is carried out using the Python programming language as a calculation tool. The developed code divides the Simulated Annealing Algorithm into two variants: Classic and Modified. The Classic variant refers to a more traditional and simple approach, using insertion operations in the job sequence as a mutation method. Meanwhile, the Modification variant makes several adjustments, including changes to the temperature function, use of different iterations, and modification of the probability function. In the final analysis, the makespan value resulting from the modified algorithm code is chosen as the best makespan value. This shows that the modified variant is considered more effective in optimizing production schedules. Figures 3, 4, and 5 show the output results from applying the Simulated Annealing Algorithm in Python as a tangible illustration of how well this technique works to solve challenging production scheduling issues.

```
Number of tasks:  6
Number of machines:  4
Tasks:
 [[129.88  56.58  68.17  50.74]
 [106.46  52.22  58.75  27.54]
 [ 81.38  41.39  41.13  23.7 ]
 [ 59.38  44.99  54.66  27.27]
 [ 55.62  31.19  57.36  20.45]
 [ 38.77  26.16  41.1   13.33]]
Classical
Best sequence:  [1, 0, 3, 5, 4, 2]
Best Cmax:  579.0400000000001
Midificated
Best sequence:  [0, 4, 3, 1, 2, 5]
Best Cmax:  569.6700000000001
<ipython-input-9-f0da30e480c0>:43: RuntimeWarning: overflow encountered in scalar divide
  prob = math.exp((Cold-Cnew)/Temp)
```

Figure 3 Demand 1 simulated annealing

```
Number of tasks:  6
Number of machines:  4
Tasks:
 [[148.43  64.66  77.91  57.99]
 [123.63  60.64  68.22  31.98]
 [ 96.46  49.05  48.75  28.09]
 [ 67.86  51.41  62.47  31.16]
 [ 64.59  36.22  66.61  23.75]
 [ 45.95  31.    48.71  15.79]]
Classical
Best sequence:  [4, 3, 5, 0, 1, 2]
Best Cmax:  672.81
Midificated
Best sequence:  [1, 4, 0, 3, 2, 5]
Best Cmax:  663.27
<ipython-input-12-f0da30e480c0>:43: RuntimeWarning: overflow encountered in scalar divide
  prob = math.exp((Cold-Cnew)/Temp)
```

Figure 4 Demand 2 simulated annealing

```
Number of tasks:  6
Number of machines:  4
Tasks:
 [[166.98  72.74  87.65  65.24]
 [140.8   69.06  77.7   36.43]
 [111.53  56.72  56.37  32.47]
 [ 76.35  57.84  70.28  35.06]
 [ 73.57  41.25  75.86  27.05]
 [ 53.13  35.84  56.33  18.26]]
Classical
Best sequence:  [5, 1, 0, 3, 2, 4]
Best Cmax:  766.5199999999999
Midificated
Best sequence:  [0, 1, 4, 3, 2, 5]
Best Cmax:  756.91
<ipython-input-15-f0da30e480c0>:43: RuntimeWarning: overflow encountered in scalar divide
  prob = math.exp((Cold-Cnew)/Temp)
```

Figure 5 Demand 3 simulated annealing

Table 4 shows the results of scheduling calculations using the Simulated Annealing method for three different demand scenarios. There has been a significant increase in line with increasing demand. From Demand 1 to Demand 2, the increase was 93.6 minutes (16.4% increase). From Demand 2 to Demand 3, the increase was 93.64 minutes (14.1% increase). This relatively consistent increase in makespan indicates a nearly linear relationship between increased demand and total production time. The job sequence varies for each request level, indicating that Simulated Annealing dynamically adjusts the sequence to optimize Makespan. Job 6 is always in last position, which may indicate the special characteristics of this job. Positions Job 1, Job 2, and Job 5 tend to be in the starting order, although the specific positions vary.

Table 4 Makespan and job sequence for simulated annealing method

Demand Variations	Makespan (minute)	Job Sequence
Demand 1	569.67	J1 - J5 - J4 - J2 - J3 - J6
Demand 2	663.27	J2 - J5 - J1 - J4 - J3 - J6
Demand 3	756.91	J1 - J2 - J5 - J4 - J3 - J6

The Simulated annealing method shows flexibility in adjusting job sequences for various levels of demand, which can result in better production efficiency. Changing the job sequence shows that this method considers the specific characteristics of each job and the level of demand in optimizing the schedule. Despite the order change, the increase in makespan remains significant, indicating that production capacity may need to be increased to accommodate higher demand. When compared with the initial method, Simulated Annealing is likely to produce a lower makespan and a more optimal job sequence.

4.3 Tabu Search (TS) method

The Tabu Search (TS) in calculating makespan and determining job sequences is an optimization method that searches for the optimal job sequence to minimize the total completion time (makespan), uses a tabu list to avoid newly explored solutions, generates and evaluates neighboring solutions by swapping job positions, accept better or less tabu solutions, and iterate the process to find the best solution. The results of makespan calculations made using Visual Basic 6.0 and the TS technique are displayed in Figure 6, Figure 7, and Figure 8. The results of the work sequence and makespan for three demand variations are derived from the Visual Basic 6.0 results.

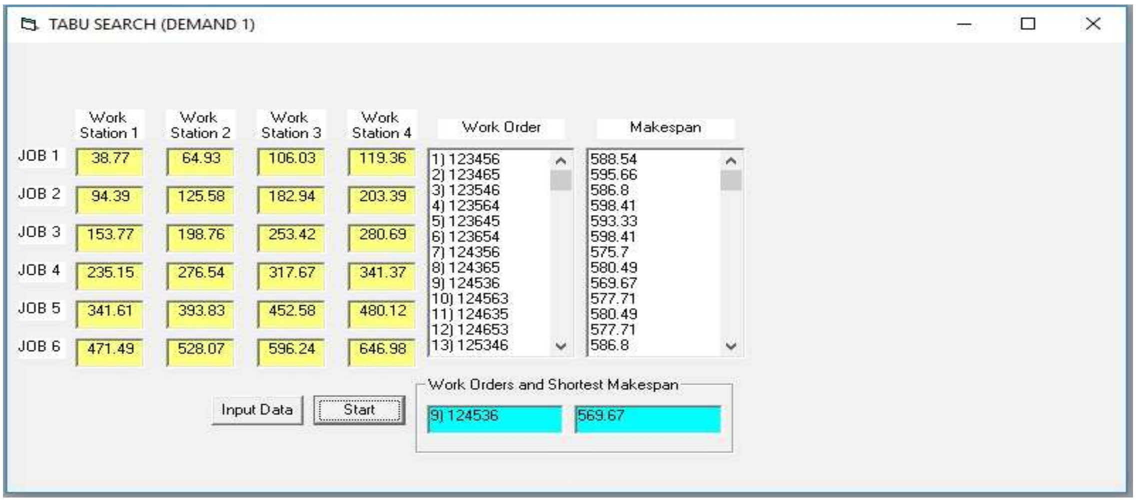

Figure 6 Demand 1 tabu search

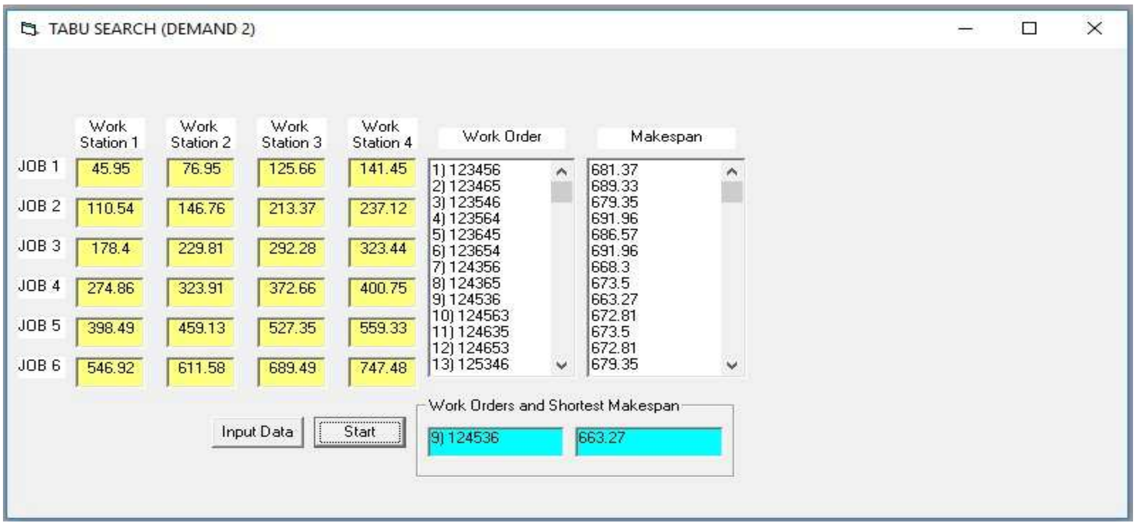

Figure 7 Demand 2 tabu search

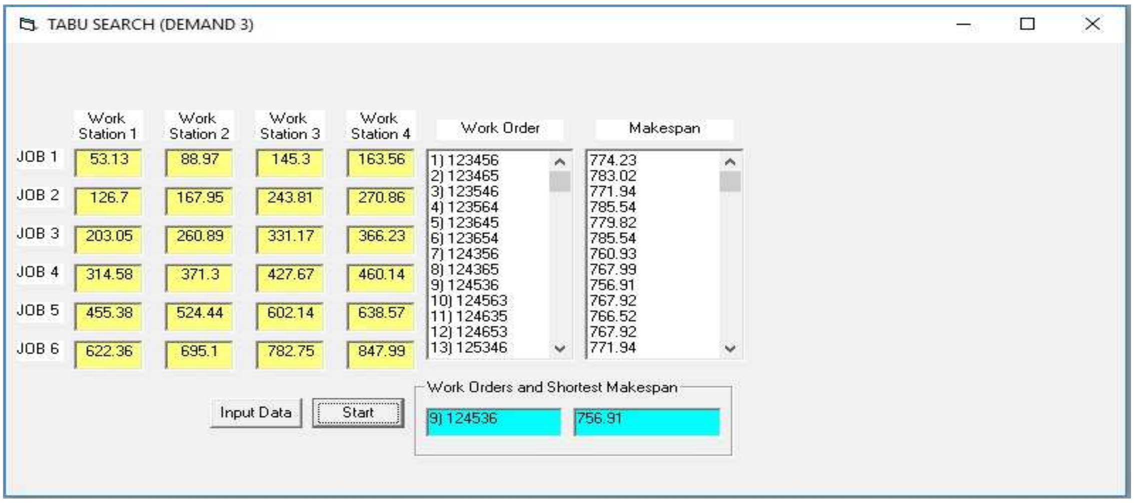

Figure 8 Demand 3 tabu search

Table 5 shows the results of applying the Tabu Search method for job scheduling with three different demand scenarios. For the three demand variations, the Tabu Search method produces the same job sequence. This indicates that this sequence tends to be optimal or near optimal for various levels of demand. It can be seen that makespan increases as demand increases. This is logical because higher demand usually requires longer production times. Sequence consistency indicates a consistent job sequence indicating that this sequence may have a structural advantage in minimizing idle time between workstations. The rise in makespan from Demand 1 to Demand 2 (16.4%) and from Demand 2 to Demand 3 (14.1%) demonstrates that the relationship between the rise in production time and the rise in demand is not necessarily linear.

Table 5 Makespan and job sequence tabu search method

Demand Variations	Makespan (minute)	Job Sequence
Demand 1	569.67	J1 - J2 - J4 - J5 - J3 - J6
Demand 2	663.27	J1 - J2 - J4 - J5 - J3 - J6
Demand 3	756.91	J1 - J2 - J4 - J5 - J3 - J6

The efficiency improvement at higher demand levels despite the disproportionate increase in makespan, indicating a robust solution applicable across various demand scenarios. The TS method showcased in the research demonstrates its capability to manage demand variations without altering the job sequence, offering significant utility in production planning [32]. This approach not only optimizes makespan but also ensures adaptability to fluctuating demand levels, enhancing operational flexibility and efficiency in production scheduling. The consistent job sequence for different demand levels underscores the method's resilience and effectiveness in addressing dynamic production requirements, making it a valuable tool for optimizing scheduling processes in diverse manufacturing environments [33].

4.4 Comparison of makespan values

Table 6 shows makespan data which shows a comparison between three scheduling methods, namely the Initial Method, Simulated Annealing, and Tabu Search, for three different demand scenarios.

Table 6 Comparison of makespan values

Method	Demand 1 (minute)	Demand 2 (minute)	Demand 3 (minute)	Job Sequence
Initial Method	588.54	681.38	774.22	Same for every demand
Simulated Annealing	569.67	663.27	756.91	Not the same for every demand
Tabu Search	569.67	663.27	756.91	Same for every demand

The Initial method produces the highest makespan for all scenarios, while Simulated Annealing and Tabu Search show identical and better performance. These two methods succeeded in reducing makespan by 3.2% for Demand 1, 2.7% for Demand 2, and 2.2% for Demand 3 compared to the Initial Method. Although these improvements may seem small, in the context of large-scale production, even small reductions in makespan can result in significant savings. The increase in makespan as demand increases is seen consistently across all methods, with an increase of around 16.4% from Demand 1 to Demand 2, and 14.1% from Demand 2 to Demand 3. This shows that all methods respond proportionally to the increase in workload. Additional information about the job sequence provided is obtained based on the three methods used:

- The Initial Method produces the same job sequence for each demand.
- Simulated Annealing produces a different job sequence for each demand.
- Tabu Search produces the same job sequence for each demand.

This shows that Simulated Annealing is more flexible in responding to changes in demand, while Tabu Search finds a more consistent solution. Nevertheless, both methods produce identical makespan, indicating that both are able to achieve optimal or near-optimal results through different approaches. Based on these results, both Simulated Annealing and Tabu Search can be recommended as effective optimization methods for this problem. Both outperform the Initial Method in terms of makespan minimization. The choice between these two methods may depend on user preference:

- If flexibility in responding to changes in demand is considered important, Simulated Annealing may be preferred.
- If job sequence consistency is considered important for long-term planning, Tabu Search may be a better choice.

For practical implementation, it is recommended to:

- Adopt Simulated Annealing or Tabu Search as a replacement for the Initial Method.
- Carry out further analysis to understand the implications of the differences in job sequences produced by Simulated Annealing.
- Consider factors such as solution stability, computing time, and ease of implementation in final method selection.

In conclusion, although both metaheuristic methods show similar performance in terms of makespan, the difference in the sequence of generated jobs can be an important factor in the choice of method depending on the specific needs of the production system. Simulation and digital technologies have significant potential in facilitating comprehensive product life cycle management. Its capabilities cover various stages, starting from the initial stage of product development, continuing to the innovative production system design stage, to the process of perfecting the production system that is already running [34]. With an emphasis on cutting overall production time and raising throughput, optimizing the makespan value in the Toyota Production System is essential to enhancing the effectiveness of logistics and production systems [35]. The approach used in this research focuses not only on reducing production time, but also on better synchronization between various processes in the supply chain, which in turn optimizes the flow of materials and information, and reduces waste in a lean production system

5 Conclusions

In order to optimize production schedules for six different types of vehicles at four workstations with three distinct demand situations, this study examines three production scheduling methods: the Initial Method, the Simulated Annealing (SA) method and Tabu Search (TS) method. The findings demonstrate that, on average, the TS and SA methods yield shorter makespan times than the Initial Method, with a reduction of around 3.2% for Demand 1, 2.7% for Demand 2, and 2.2% for Demand 3. Although the SA method and TS method produce lower makespan identical, they differ in approach, namely the SA method produces a different job sequence for each level of demand, showing flexibility in responding to changes in demand. Meanwhile, the TS method produces consistent job sequences for all demand levels, indicating the stability of the solution. The increase in makespan as demand increases is consistent across all methods (approximately 16.4% from Demand 1 to 2, and 14.1% from Demand 2 to 3), indicating a proportional response to increasing workload. In conclusion, both the SA method and the TS method are recommended as effective optimization methods, outperforming the Initial Method. The choice between the two depends on the preference between the flexibility of the SA method or the consistency of the TS method in scheduling. Practical implementations must consider factors such as solution stability, computing time, and ease of implementation. The next potential research is an in-depth analysis of the trade-off between the flexibility of the SA method and the consistency of the TS method in the context of long-term scheduling. The SA method offers flexibility with a varying work sequence according to demand, while the TS method provides consistency with a fixed sequence. Explore the combination of the SA method and the TS method to utilize the advantages of each method. Apply this method to more complex production scenarios, for example with more types of products or workstations.

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Supply chain resilience in the face of uncertainty: a study of wheat trade and supply chain optimization

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Keywords: supply chain resilience, risk management, disruption, optimization, global trade.
Abstract: This research paper explores the impact of disruptions such as the COVID-19 pandemic, Russia's invasion of Ukraine, and extreme weather events on global supply chains, with a focus on the grain trade. The paper reviews recent studies on supply chain resilience and risk management, highlighting the need for a comprehensive approach to managing supply chain risks. In an attempt to combine global wheat trade with supply chain resilience, this study proposes an optimization model to help supply chain professionals to pick from a variety of robust and resilient approaches. This proves the investigation of whether such a process ensures the best choice challenging, which might be a combination of both resilient and robust approaches. The author concentrates on the extreme weather and ban on exports disruptions, in order to acquire sufficient depth in the inquiry. A numerical case study of a real-world wheat supply chain is used to apply the model. The outcomes suggest that the best method for reducing the risks of supply-side disruption is a mixed combination of robust and resilient approaches.

1 Introduction to supply chain resilience

With the COVID-19 pandemic, the follow-up shipping and air freight troubles, and Russia's invasion of Ukraine, measuring supply chain efficiency and understanding its factors seem more crucial than it was. Demand for several products, such as electronics and household appliances, increased during the pandemic, but supply and transportation capacity decreased. For instance, the request for microprocessors, a key element in integrated circuit technology and the majority of manufacturing industries, increased, but their supply was constrained by the pandemic's effects as well as droughts and accidents at several important production locations. The pandemic hindered the availability of port and warehouse workers, truck drivers, train engineers, and other personnel in several nations, and it confounded crew adjustments on ships. Additionally, some nations implemented strong zero-COVID regulations that included thorough local lockdowns [1].

Furthermore, due to the suspension of exports from Belarus, Russia, and Ukraine following Russia's invasion of Ukraine, prices for food and energy had risen. This led to cascading repercussions including overshooting demand and export limits. When the majority of services to and from Russia were halted, container shipping was impacted. Flights across Russian airspace and container rail facilities concerning Europe and Asia via Russia were among the many commerce and transportation links that Belarus and Russia had with Europe.

As far as global seaborne grain trade is concerned, it experienced significant pressure in Q2 2022 from the Russia-Ukraine conflict and a slower start to the year for North American grains exports. During October 2022, however, a range of factors including the Black Sea Grain Initiative and a strong Brazilian corn harvest have helped to shape a more positive second half of the year for grain trade trends. After a strong period of growth in seaborne grain trade, 2022 presented significant challenges for the sector. Ukrainian grain accounted for 10% of global seaborne grain trade in 2021 but were effectively suspended by Russia’s invasion. Simultaneously, poor growing conditions undermined North American output; US wheat yields were down over 10% in the 2021-22 season and exports in 1H 2022 fell by 26% [2].

In November 2022, there had been some positive changes. Grain exports from the Ukrainian ports of Chornomorsk, Odessa, and Yuzhny started to ramp up from the beginning of August following the ratification of an UN-backed initiative between Ukraine, Turkey, and Russia. The initiative established a maritime corridor to facilitate the movement of foodstuffs. Elsewhere, other factors had also offered support. Brazil had been on track for a record corn harvest in 2022, with exports hitting a record in August, up 14%, while improved US and EU grain exports had also lent support at times. However, the geopolitical situation in Ukraine remained fluid and there is uncertainty around the renewal of the Black Sea Grain Initiative on 19th November 2022 in the midst of the peak Q4 harvest and export seasons for wheat and corn in the Black Sea region. Nonetheless, positive developments in Ukraine and beyond in end 2020 had set up a more positive second half of the year for seaborne grain trade, lending welcome support for smaller bulk carriers in particular [2].

In an attempt to combine global wheat trade with supply chain resilience, the author responds to the following research inquiries: which robust/resilient approaches are successful at reducing the risks associated with extreme weather and ban on export disruptions? How would the aforementioned disruptions affect the efficacy of robust/resilient approaches? How may businesses leverage global wheat trade to build a more resilient supply chain that can better withstand the challenges of an uncertain and fast-changing global marketplace?

This study proposes an optimization model to help supply chain professionals to pick from a variety of robust and resilient approaches. This proves the investigation of whether such a process ensures the best choice challenging, which might be a combination of both resilient and robust approaches. The author concentrates on the extreme weather and ban on exports disruptions, in order to acquire sufficient depth in the inquiry. To begin with, worldwide, ports, roadways, and factories are being hit harder and harder by extreme weather, from floods to wildfires. For example, late in August 2022, factories in China were closed; this had been common in a nation that had enacted sporadic lockdowns to combat the pandemic. However, the pandemic was not to blame that time; instead, a record-breaking drought damaged the economy in southwest China, stopping global supply chains for goods like electronics, cars, and other items that had been regularly interrupted during the previous three years [3]. Secondly, the ban on exports leads in a substantially longer than typical supply delay. For example, during summer 2022, major nickel producer Indonesia imposed a complete export prohibition, while the Philippines imposed non-automatic licensing. Australia put a stop to the shipment to Russia of alumina, a key component in the manufacturing of aluminum, on March 19, 2022 [4].

This paper makes an effort to close the empirical gap in prior research on the subject and throw some light on potential policy ramifications for supply chain professionals. It suggests a comprehensive and clearly stated practical context to choose risk management approaches from a group of reliable/durable ones. The framework meets supply, demand, and shipping capacity restrictions while maximizing anticipated net income. The remainder of the study is structured as follows: section 2 briefly reviews the relevant literature and emphasizes the research gap. Section 3 develops and explains the innovative methodological framework with an application to wheat production in India. Results are presented in Section 4 once a quantitative case study using the model is completed. Section 5 critically discusses major empirical findings.

2 Supply chain risk management and resilience: a review of the literature

By creating treatments that let a supply chain react to a disruption while regaining its prior operational state or better, supply chain resilience lessens the impact of disruptions. Being more responsive to unforeseen variables in the corporate environment has drawn increasing attention recently as one of a firm's key features [5]. In other words, the competence of a corporation to endure a disruption, return to its pre-disturbance state after the disruption, can even move in the direction of a more ideal state subsequently to the disruption is what is meant by resilience in a supply chain. There is a plentiful of studies that have reached this matter; the author chose to focus on the most recent ones. [6] investigated a hybrid methodology to supply chain risk reduction that made use of both process flexibility and finished goods inventories. Modeling of the interaction between inventory and process flexibility involved a two-stage robust optimization issue. According to authors, prior to a disruption, the company allocates inventory in the first stage; in the second stage following a disruption, to prevent demand loss, the corporation determines the production amounts at each plant. They give a formula for the ideal inventory solution based on analysis for flexibility designs, which enables to investigate the efficacy of various degrees of flexibility. Furthermore, they discover that firms should allocate more inventory to high variability products when flexibility is low.

[7] developed planning for supply chain risk management based on metrics for risk readiness and resiliency, while integrating a mathematical model that took into account the selected risk variables, containment strategies, and expected benefits for supply chain planning. In order to achieve the intended performance goals, their research additionally led to the suggestion of a method for conducting what-if evaluations of the many trade-off possibilities relevant to different levels of risk preparation and resiliency. In a similar content, [8] investigated a holistic approach to supplier choice, demand distribution, and transportation selection for channels in a situation with delivery reliability and hazards of supplier and geographical disruption. The authors claimed that their proposed model helped stakeholders understand how supply chain risk management uses the aforementioned elements to improve reaction to different kinds of disruption. Utilizing a decision tree and two-stage mixed-integer coding model, the importance of considering contingency planning in order to decrease the negative consequences of disruptions was investigated. Also highlighted were the effects of geographical and supplier reliability, along with the delay cost parameter, on management decisions about demand allocation.

A hierarchy-based framework for supply chain resilience was developed by [9], supporting the interactions between the 13 enablers that were taken into consideration and empirically validating the model. The path analytical model was tested and the hierarchical model was validated using structural equation modeling. The authors used Matrix of Cross Impact Multiplications Applied to Classification methodology to classify the enablers according to their driver power and dependence. Their main finding was that by altering their strategic assets and using the suggested strategy, businesses can boost their resilience potential. Their concept uses a single quantitative index to measure resilience, while comparison is done using the coefficient of similarity. Additionally, [10] investigated the durability of physical internet-based inventory models in the face of disturbances at supply chain facilities. An experimental quantitative investigation was presented to answer the topic using an optimisation model based on simulation. Their experimental findings demonstrated that for demand uncertainties and supply chain disruptions, the physical internet inventory model outperforms conventional pre-determined inventory control approaches. Additionally, as product value, penalty costs, and disruption frequency rise, the performance gap widens. They argue that the advantages are mostly due to the improved agility, flexibility, and delivery alternatives made possible by the connected logistics services.

All businesses must be responsive to consumers and markets. By looking at the main causes and impacts of supply chain agility at the strategic as well as operational levels through the prism of resources, [11] made an attempt to address this problem. They contended that two organizational flexibility aspects are the essential precursors to supply chain agility. Additionally, manufacturing flexibility, strategic flexibility, and supply chain agility are all important aspects of company performance. Through an empirical study of a few chosen industrial practitioners, they developed and evaluated a conceptual framework for the arguments. Structural equation modeling was used to examine data from a sample of 141 clothing manufacturing firms. Their findings showed that supply chain agility was positively influenced by both strategic and manufacturing flexibility. However, manufacturing flexibility had no effect on a firm's performance, whereas strategic flexibility did.

Following a similar conceptual framework, [12] examined the effects of supply risk and demand risk on a supply chain with numerous locations, transportation routes, and product projection over a number of time periods. They used a quantitative example to illustrate the link amongst three measurable features related to responsiveness, risk, and the cost of new and seasonal commodities before looking at how flexibility and agility may be employed to lessen supply chain disruptions. In order to show a trade-off between objective functions in their quantitative example, they used three multi-objective optimization techniques to decompose the multi-objective mixed integer programming model.

3 Supply chain risks and the importance of risk management: defining the problem

Supply chain risks could have some potentially severe consequences if they are not swiftly mitigated. Risks to employee health and safety, hacking, criminal activity, issues with suppliers, along with natural disasters could have an impact on the company's supply chain. A company's financial stability, standing in the market, and the well-being of the people and things associated with the production cycle are all subject to risks. If risks materialize and affect final goods or services, the company may experience a deluge of disgruntled clients, which could hurt sales and image. So, supply chain risk management is crucial if the company is to successfully protect its brand and bottom line. Risks should be evaluated at each step of the production flow, and safety precautions should be put in place to guard against weaknesses or interruptions.

A supply chain network strategic-tactical planning issue is the topic of the suggested study. The best risk management approaches must be chosen at the strategic level from a blend of robust and resilient approaches. The author concentrates on two leading supply-side disruption risks: extreme weather and ban on exports disruptions. The author considers the three following approaches, which are probably successful in reducing risks associated with these two types of disruption [12,13][1]:

(i) Supply diversification (SD) - Utilizing a single supplier concentrates risks, and any problems with the supplier increase the likelihood that the complete supply chain will be disrupted. The company can spread risks and lessen risk effect by diversifying its supplier base. Increased supply chain resilience may be aided by a larger supplier network. Engaging several suppliers, and if practical, suppliers in various areas, can help lower the risk of locally specific problems, regardless of whether the company has a global supply chain or a relatively contained production flow. Choosing vendors and contractors with particular expertise, finding goods and services at the best costs while simultaneously maintaining the highest quality and profitability are all made possible by working with many suppliers.

(ii) Supply Chain Risk Management Plans (SCRMP) - As with all other parts of risk management, risk evaluations are essential to supply chain risk management. The company must determine, evaluate, and finally be ready for any risks that could disrupt the supply chain. Outline the precautions that should be taken to limit risks throughout the production process and be ready to take action in the event of foreseeable occurrences or risks that could have a negative effect on the supply chain. The firm should make processes adaptable so they may be changed as needed to minimize supply chain disruptions. It's critical to remember that not every circumstance can be predicted and planned for. Therefore, the supply chain risk management strategy should prioritize based on frequency and probable consequences and set restrictions and backup plans in place

[1] Apart from the approaches unfolded here, the author would suggest as future research two more approaches: (a) Monitor market trends, namely keep track of the latest market trends, such as the availability of wheat, prices, and demand. This helps anticipate changes that may affect supply, including weather, political instability, or other factors and (b) invest in technology, since technology can help optimize supply chain efficiency and resilience. For instance, using predictive analytics or blockchain technology can enhance traceability and transparency, enabling better data management across the supply chain.

for scenarios that are most likely to happen or that will significantly harm business.

(iii) Backup Suppliers (BS) - Precautionary action is essential in risk management for effective risk assessment and strategic risk mitigation. Risk management in the supply chain is also crucial. The business must take a proactive stance. By preparing for probable outcomes of an incident, the organization can ensure business continuity and protect itself from threats both inside and outside. Any time could come when one of the company's business partners would be unable to carry out their responsibilities in the supply chain. Vendors could be unable to complete an order for a number of different reasons. For example, they might be dealing with unusually high demand or problems in their own supply chain. For one cause or another, such as a supplier's bankruptcy, they may even decide to stop operations. By rapidly bringing on alternative business partners, the company can avoid significant disruptions and delays if it encounters problems with any of its suppliers. Therefore, the company should confirm that it has backup vendors prepared before any issues arise. The same procedures it would use to select a main supplier should be used to find suitable suppliers. After choosing a supplier, to reserve production capacity in case it's needed during a business disruption, the company ought to optimally negotiate an agreement with them. This will make it possible for the business to respond more quickly to issues. As an alternative, it can merely inform suppliers that they will be kept on file in case of emergencies, but the company runs the risk of their availability being limited.

(iv) Risk acceptance ($\boldsymbol{r_0}$) - The author takes into account a risk acceptance approach for comparison's sake. A managerial choice to forgo taking major action to mitigate a particular risk is known as risk acceptance. It refers, in more detail, to the process by which a specific risk is accepted by an entity. When someone or something accepts a risk, they are acknowledging that there is a possibility of losing money. The most common defense is that other risk management approaches, including risk avoidance or risk restriction, might be more expensive than the risk itself.

To represent perishability, the author uses a fractional formulation. However, the proportion employed is commodity-dependent rather than fixed or time-dependent, as indicated by $\boldsymbol{\rho(c)}$. The perishability function relies on the following factors in addition to the perishability fraction: c is the commodity's type; $\boldsymbol{t_0}$ denotes the moment at which it enters a specific level of the network; and $\boldsymbol{\Delta_t}$ demonstrates the length of time it stays there. The author takes homogenous perishability into account because such a network frequently uses air-cool storage. The definition of the perishability metric can be seen in (1):

$$\lambda_n(c,t_0,\Delta_t) = \lambda_{yz}(c,t_0,\Delta_t) = \lambda(c,t_0,\Delta_t) = \prod_{t=t_0}^{t_0\Delta_t}(1-\rho(c)) = (1-\rho(c))^{\Delta_t}, \tag{1}$$

where:

$y \in Y$: is one (y) of the supply sites Y, comprising a collection of growers, packing and storage facilities.
$z \in Z$: is a demand location z, for example a demand market within the set of demand locations Z.
$\lambda_y(c,t_0,\Delta_t)$: is the supply-side storage $y \in Y$ for product $c \in C$ that enters in period $t_0 \in T$ for Δ_t periods' unperished fraction function.
$\lambda_z(c,t_0,\Delta_t)$: is the demand-side storage $z \in Z$ for product $c \in C$ that enters in period $t_0 \in T$ for Δ_t periods' unperished fraction function.
$\lambda_{yz}(c,t_0,\Delta_t)$: is the transportation storage yz $(y \in Y, z \in Z)$ for product $c \in C$ that enters in period $t_0 \in T$ for Δ_t periods' unperished fraction function.

With a constant exponential product dependent loss rate, the only factor affecting the unperished fraction is the length of time that inventory is held or shipped. This is a good spot to start because businesses almost always have outdated inventory. Inventory that is out of date must be identified as such. Contrary to wine, goods or basic materials kept in storage do not get better with age. When something has been kept for six months or longer and a short-term use is not anticipated, it should be thrown away [14]. Because their management does not want to disclose the ensuing loss on their financial statements, troubled companies are hesitant to do this. The author does set an upper-bound on the maximum duration, though. All items that are older than six months will be deemed perished.

The author refers to a wheat sack as a product unit in this issue[2]. As a result, wheat sacks are used to quantify all quantity-related parameters and variables. All factors and variables related to unit cost and price are calculated per wheat sack. Following [15], the algorithm makes the following presumptions as well: (i) at the expiration of a time period, all shipments ($\boldsymbol{x_{yzct_\psi}}$) are fulfilled; (ii) the sales price is obtained from the market and is used as an input parameter; it is the price of product c in market z at time t under event ψ; (iii) only during the phases of

[2] The weight of one sack of wheat is considered 85kg (1 bushel = 27kg).

inventory holding and shipping, denoted by $\boldsymbol{\lambda_z(c,t-1,1)}$ and $\boldsymbol{\lambda_y(c,t+d(y,z)-1,1)}$ for supply-side and demand-side inventory holding, respectively, and by $\boldsymbol{\lambda_{yz}(c,t,d(y,z))}$ for shipping (where $\boldsymbol{d(y,z)}$ denotes the delivery lead-time between y and z) is the decomposition process taken into account on the supply; (iv) at the expiration of a time period, products that have perished or are older than six months are thrown away; (v) at every supply domain, disruptions happen one at a time.

The two-stage stochastic programming approach, in which the degree of uncertainty is only partially exposed, is the most common type of stochastic programming. The choice variables in these issues are divided into two groups, the first-stage and the second-stage decisions [16,17]. This study's two-stage stochastic model follows this pattern. The first-stage decisions are made before the identification of the uncertain parameters, which occurs in the second stage, i.e. shipment, inventory combined in $\boldsymbol{X_{\psi t}}$ prior to $\boldsymbol{\tilde{t}(\psi)}$, where:

$\boldsymbol{g_r}$: Binary variable for choosing approach r.
$\boldsymbol{X_{\psi t}}$, t< $\boldsymbol{\tilde{t}(\psi)}$: Set of tactical variables prior to event completion.

In this instance, the second-stage decisions or recourse actions have a corrective effect in addition to reducing the impossibilities imposed on by the identification of the uncertain parameters. The overall purpose is to maximize both the objective function of the first-stage costs and the expected return of the random second-stage costs. These variables are established after an event is realized. These are tactical supply chain judgments $(\boldsymbol{X_{\psi t}})$ in time-periods after $\boldsymbol{\tilde{t}(\psi)}$, where:

$\boldsymbol{X_{\psi t}}$, t≥ $\boldsymbol{\tilde{t}(\psi)}$: Set of tactical variables following event completion.

Following [18] and [19], given each event $\psi \in \Psi$, equation (2) defines the profit $(V_\psi(X_\psi))$ under event-dependent tactical choices of $X_\psi \equiv \{X_{\omega t}, t \in T\}$:

$$V_\psi(X_\psi) = \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} v(z,c,t,\psi)h_{zct\psi} - \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^m(z,c,t)m_{zct\psi} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T}\sum_{r\in\xi^\kappa\cup\{r_0\}} s^\kappa(y,c,t,\rho)\kappa_{yct\psi r} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T} s^m(y,c,t)m_{yct\psi} - \sum_{y\in Y}\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^x(y,z,c,t)x_{yzct\psi} \quad (2)$$

where:
$z \in Z$: is a demand spot *z*, for example a demand market within the set of demand locations *Z*.
$c \in C$: is a commodity c within the set of commodities *C*.
$t \in T$: is one of the times *t* in the group of periods *T*.
$y \in Y$: is one (*y*) of the supply sites *Y*, comprising a collection of growers, packing and storage facilities.
$r \in \xi^\kappa \cup \{r_0\}$: is a approach *r* within the group of all approaches *ξ*.
ξ^κ : is the set of risk management approaches related to supply status.
$v(z,c,t,\psi)$: is the market value for commodity $c \in C$ at demand spot $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$s^m(y,c,t)$: is the storage cost per unit of commodity $c \in C$, when held at supply spot $y \in Y$ for one period, from period $t \in T$.
$s^\kappa(y,c,t,\rho)$: is the purchase cost per unit of commodity $c \in C$ at supply spot $y \in Y$, in period $t \in T$, in approach $r \in \xi$.
$s^x(y,z,c,t)$: is the shipping cost between $y \in Y$ and $z \in Z$ per unit of commodity $c \in C$ in period $t \in T$.
$h_{zct\psi}$: is the sales of commodity $c \in C$ at demand spot $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$x_{yzct\psi}$: is the transportation of commodity $c \in C$ from supply spot $y \in Y$ to demand spot $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$m_{yct\psi}$: is the inventory of commodity $c \in C$ held at supply spot warehouse $y \in Y$ in period $t \in T$, under event $\psi \in \Psi$.
$m_{zct\psi}$: is the inventory of commodity $c \in C$ held at demand spot warehouse $z \in Z$ in period $t \in T$, under event $\psi \in \Psi$.
$\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} p(z,c,t,\psi)h_{zct\psi}$: denotes the sales revenue, namely the money the company makes from selling products.
$\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^m(z,c,t)m_{zct\psi}$: denotes the storage cost at demand spots, namely the sum of money expended on storing (holding) inventory at demand spots.
$\sum_{y\in Y}\sum_{c\in C}\sum_{t\in T}\sum_{r\in\xi^\kappa\cup\{r_0\}} s^\kappa(y,c,t,\rho)\kappa_{yct\psi r}$: denotes the supply expenses, namely the cost of consumables used during a reporting time.
$\sum_{y\in Y}\sum_{c\in C}\sum_{t\in T} s^m(y,c,t)m_{yct\psi}$: denotes the storage cost at supply spots, namely the sum of money expended on storing (holding) inventory at supply spots.
$\sum_{y\in Y}\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^x(y,z,c,t)x_{yzct\psi}$: denotes the shipping cost, namely physical transportation, handling, customs, tariffs, inspection, storage, insurance, and taxes, as well as all related fees and expenses.

Following [12], the cost of implementing a risk management plan (g_r) is a fixed cost (f_r). Equation (3) gives the overall cost of putting risk management approaches $F(g_r)$ into practice. The choice of a mixed collection of robust/resilient approaches comes with technical challenges. The author categorizes all robust/resilient approaches as being supply-based $(r \in \xi^{\kappa})$ and probability-based $(r \in \xi^{pr})$ in order to surmount the difficulties. At least one of these two sets must include the specified approach. A risk acceptance approach (r_0) can be used regardless of the specified approach sets [20].

$$F(g_r) = \sum_{r\in\xi} f_r g_r \tag{3}$$

As shown in Equations (4) and (5), both the supply cost $s^{\kappa}(y,c,t,\rho)$ and the supply bounds are impacted by supply-based approaches. Supply bounds are multiplied by a term (g_r) associated with the author's approach-selection decision variable wherever they occur in the model constraints.

$$\underline{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^{\kappa}} g_r\right) \le b_{yct\psi r_0} \le \overline{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^{\kappa}} g_r\right) \tag{4}$$

$$\underline{b}(y,c,t,\psi,r)g_r \le b_{yct\psi r} \le \overline{b}(y,c,t,\psi,r)g_r \tag{5}$$

where:

$\underline{b}(y,c,t,\psi,r_0)$: is the lower bound for supply $c \in C$ at supply spot $y \in Y$ at period $t \in T$ under event $\psi \in \Psi$ when employing approach $r \in \xi^{\kappa} \cup \{r_0\}$.

$\overline{b}(y,c,t,\psi,r_0)$: is the upper bound for supply $c \in C$ at supply spot $y \in Y$ at period $t \in T$ under event $\psi \in \Psi$ when employing approach $r \in \xi^{\kappa} \cup \{r_0\}$.

Although this may happen in reality, the model does not permit the selection of more than one supply-based approach due to the interaction of supply bounds. To deal with this constraint, the author outlines a joint approach $BS = BS \cap SD$ in the supply-based approach set. On the other hand, the chance of a disruption $(Pr(\psi))$ is decreased by probability-based approaches $r \in \xi^{pr}$, while the likelihood of the base event $(Pr(\psi_0))$ is increased. Therefore, there are probability changes $\Delta Pr(\psi,r)$ for each $r \in \xi^{pr}$ for every $\psi \in \Psi$ that have an impact on the anticipated overall profit. A risk management plan can only choose one probability-based approach to avoid the interaction of the probability adjustments (Hopkin, 2018). This can be transformed to equation (6).

$$\sum_{r\in\xi} l_r g_r + \left[Pr(\psi_0) + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r)g_r\right] V_{\psi_0}(X_{\psi_0}) + \sum_{\psi\in\Psi\setminus\{\psi_0\}}\left[Pr(\psi) - \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r)g_r\right] V_{\psi}(X_{\psi}) =$$
$$= \sum_{r\in\xi} l_r g_r + \sum_{\psi\in\Psi} \Pr(\psi) V_{\psi}(X_{\psi}) + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r)g_r V_{\psi_0}(X_{\psi_0}) - \sum_{\psi\in\Psi\setminus\{\psi_0\}}\sum_{r\in\xi^{pr}} \Delta Pr(\psi,r)g_r V_{\psi}(X_{\psi}) \tag{6}$$

where:

$\sum_{r\in\xi} l_r g_r$: the fixed cost for risk management.

$\left[Pr(\psi_0) + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r)g_r\right] V_{\psi_0}(X_{\psi_0})$: the adjusted performance for base alternative

$\sum_{\psi\in\Psi\setminus\{\psi_0\}}\left[Pr(\psi) - \sum_{r\in\xi^{pr}} \Delta Pr(\psi,r)g_r\right] V_{\psi}(X_{\psi})$: the adjusted performance for other alternatives

$\sum_{\psi\in\Psi} \Pr(\psi) V_{\psi}(X_{\psi})$: unadjusted performance for all alternatives

$\sum_{r\in\xi^{pr}} \Delta \Pr(\psi_0,r)\, g_r V_{\psi_0}(X_{\psi_0})$: adjustment to ψ_0

$\sum_{\psi\in\Psi\setminus\{\psi_0\}}\sum_{r\in\xi^{pr}} \Delta Pr(\psi,r)g_r V_{\psi}(X_{\psi})$: adjustment to other alternatives

$\sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r)g_r V_{\psi_0}(X_{\psi_0}) - \sum_{\psi\in\Psi\setminus\{\psi_0\}}\sum_{r\in\xi^{pr}} \Delta Pr(\psi,r)g_r V_{\psi}(X_{\psi})$: the method for obtaining the efficient adjustment to the anticipated profit for $r \in \xi^{pr}$.

As discussed before, two steps of decision-making are required for two-stage optimization. As a result, there are two sets of variables, the set of first-stage and the set of second-stage variables that have feasible solutions respectively, depending on the first-stage answer that has been selected [21]. The method used in this paper permits the automatic selection of one alternative for certain and uncertain two-stage events based on several choice variables. It is possible to utilize this technique to address any two-stage multi-objective optimization problem, even though the author presents it in the context of supply disruptions.

The two-stage stochastic optimization model may now be constructed using the definitions provided above. Following [18] and [22], the goal function in equation (7) optimizes anticipated profit in the event of a supply-side disruption.

$$\sum_{r\in\xi} -l_r g_r + \sum_{r\in\xi^{pr}} \Delta Pr(\psi_0,r)g_r V_{\psi_0}(X_{\psi_0}) -$$
$$- \sum_{\psi\in\Psi\setminus\{\psi_0\}}\sum_{r\in\xi^{pr}} \Delta Pr(\psi,r)g_r V_{\psi}(X_{\psi}) + \sum_{\psi\in\Psi} \Pr(\psi) V_{\psi}(X_{\psi}) \tag{7}$$

The event-dependent profit has a linear formula in limitation (8).

$$V_\psi(X_\psi) = \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} v(z,c,t,\psi)h_{zct\psi} - \sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^m(z,c,t)m_{zct\psi} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T}\sum_{r\in\xi^\kappa\cup\{r_0\}} s^\kappa(y,c,t,\rho)\kappa_{yct\psi r} - \sum_{y\in Y}\sum_{c\in C}\sum_{t\in T} s^m(y,c,t)m_{yct\psi} - \sum_{y\in Y}\sum_{z\in Z}\sum_{c\in C}\sum_{t\in T} s^x(y,z,c,t)x_{yzct\psi} \quad (8)$$

By taking into account inventory holding, shipment, and supply in balance, limitations (9) and (10) balance the movement of goods in supply-side spots.

$$\sum_{r\in\xi^\kappa\cup r_0}\xi_{yc1\psi r} = m_{yc1\psi} + \sum_{z\in Z,t+d(y,z)\le|T|} X_{yzc1\psi} \quad (9)$$

$$\sum_{r\in\xi^\kappa\cup r_0}\xi_{yct\psi r} + \lambda(c,t-1,1)\, m_{yct-1\psi} = m_{yct\psi} + \sum_{z\in Z,t+d(y,z)\le|T|} X_{yzct\psi} \quad (10)$$

The flow of goods in demand-side spots is similarly balanced by limitations (11) and (12) by taking inventory holding, shipment, and sales into account.

$$\sum_{y\in Y,d(y,z)=0}\lambda(c,t-d(y,z),d(y,z))\, x_{yzct-d(y,z)\psi} = h_{zct\psi} + m_{zct\psi} \quad (11)$$

$$\sum_{y\in Y,t>d(y,z)}\lambda(c,t-d(y,z),d(y,z))\, x_{yzct-d(y,z)\psi} + \lambda(c,t-1,1)m_{zct-1\psi} = h_{zct\psi} + m_{zct\psi} \quad (12)$$

Limitations in (13) establish the supply range for a risk-acceptance approach.

$$\underline{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^\kappa} g_r\right) \le b_{yct\psi r_0} \le \overline{b}(y,c,t,\psi,r_0)\left(1-\sum_{r\in\xi^\kappa} g_r\right) \quad (13)$$

A supply-based risk management approach has bounds on the supply that are set by the limitations in (14).

$$\underline{b}(y,c,t,\psi,r)g_r \le b_{yct\psi r} \le \overline{b}(y,c,t,\psi,r)g_r \quad (14)$$

Limitation (15) guarantees that only one supply-based approach will be chosen out of all possible alternatives.

$$\sum_{r\in\xi^\kappa} g_r \le 1 \quad (15)$$

A market capacity limitation is limitation (16).

$$\sum_{c\in C(e)} h_{zct\psi} \le \bar{j}(z,e,t) \quad (16)$$

where:
$e \in E$: a product e contained by a group of products E
$\bar{j}(z,e,t)$: the upper threshold of product $e \in E$ demand, in demand spot $z \in Z$, at time $t \in T$.

Limitation (17) guarantees that a maximum of one probability-related approach is chosen.

$$\sum_{r\in\xi^{pr}} g_r \le 1 \quad (17)$$

The limitations in (18) specify the transport capabilities.

$$\sum_{z\in Z,t+d(y,z)\le|T|} X_{yzct\psi} \le \bar{x}(y,c,t) \quad (18)$$

A non-anticipatory limitation (19) makes sure that choices made in various yield disruption situations are consistent before a disruption actually happens.

$$X_{\psi t<\tilde{t}(\psi)} = X_{\psi_0 t} \quad (19)$$

Finally, non-negative and binary variables are defined by limitation (20).

$$\underline{b}(y,c,t,\psi,r) \ge 0$$
$$h_{zct\psi} \ge 0$$
$$X_{yzct\psi} \ge 0$$
$$m_{\delta ct\psi} \ge 0$$
$$g_r \in \{0,1\}$$

where:
$\delta \in \Delta$: a location δ contained by group of all spots $\Delta \equiv Y \cup Z$.

This issue is known as a Mixed Integer Quadratic Program (MIQP) since the objective functions contain a quadratic term. A Mixed Integer Linear Program (MILP) is a problem that has an objective function (a linear objective) without any quadratic terms. According to [23] and [24], relevant quadratic terms like the aforementioned linear formula (8) could be dealt using the Big-M method to convert the model from a MIQP to MIPL. The Big M method is a version of the Simplex Algorithm that foremost observes a breadth-first search (BFS) algorithm by including artificial variables to the problem. The objective function of the original linear programming ought to be altered to guarantee that the artificial variables are all equal to 0 at the conclusion of the simplex algorithm.

The author defines additional variables $\boldsymbol{C_{\psi_0 r}}$ and $\boldsymbol{C_{\psi r}}$ as the adjustments in the anticipated profit, when $\boldsymbol{r} \in \boldsymbol{\xi^{pr}}$ if used in base-case and disruption events, respectively. The (8) is the re-ordered in (20):

$$\sum_{r\in\xi^{pr}} l_r g_r + \sum_{\psi\in\Psi}\Pr(\psi)\, V_\psi(X_\psi) + \sum_{r\in\xi^{pr}} C_{\psi_0 r} - \sum_{r\in\xi^{pr}}\sum_{\psi\in\Psi\setminus\psi_0} C_{\psi r} \quad (20)$$

The model transformation is dependent on the following extra limitations (21), (22), (23), (24).

$$C_{\psi r} - \Delta\Pr(\psi, r)V_{\psi}X_{\psi} \leq B(1 - g_r) \quad (21)$$
$$C_{\psi r} - \Delta\Pr(\psi, r)V_{\psi}X_{\psi} \geq -B(1 - g_r) \quad (22)$$
$$C_{\psi r} \leq Bg_r \quad (23)$$
$$C_{\psi r} \geq -Bg_r \quad (24)$$

where B is such a big number to impose Big-M limitations.

When an integer viable solution is available, the Branch-and-Cut method typically runs more quickly. An upper bound on the cost of the solution enhances the algorithm's capacity to prune branches from the search tree, and this solution is also utilized by local search MIP heuristics. Several heuristics are used by MIP solvers to automatically generate these solutions; however, they are not always effective. The author employed Python-MIP, which enables the creation of better Branch-&-Cut algorithms by connecting routines tailored for particular applications to the general algorithm built into the solver engine. Given that there aren't many possible occurrences in this study's problem, the Branch-&-Cut algorithm eventually solves the stochastic model's deterministic equivalent.

4 Results - numerical application and case study illustration

4.1 Production and supply of wheat in India

In India, wheat is the second most popular grain after rice. The nation is ranked as the second-largest wheat producer in the world. Commercial foods like wheat are farmed over a huge amount of land. Wheat is regarded as the food with the highest protein content for humans. India's economy depends 40% on wheat exports. India produces 70 million tonnes of wheat annually since it is the main agricultural product in the nation. Statistics show that about 12% of the world's wheat is produced in India. The decrease in wheat production in the United States (May 2022) made wheat export from India possible. However, India uses contemporary technology to meet the rising demand for wheat. India's wheat export industry is hampered by a lack of quality control, adequate processing facilities, storage space, and transportation infrastructure [25].

Incorporated in 1975, the wheat producing company Shri Mahavir Agritech (a division of the Mahavir Group) has become a leader in the production of whole wheat flour, the processing of wheat, and the supply of goods including chickpeas, semolina flour, durum wheat, milling wheat, all-purpose flour, and others. The company's cutting-edge infrastructural facility is divided into units. These units, each having particular duties and accountability are processing, quality assurance, warehousing & packaging, logistics, and administrative. It also offers this assortment in a variety of packaging solutions to match the clients' varied needs. Its ability to serve orders quickly has allowed it to build up a sizable clientele. Specifically, the company has built up a clientele network, providing services to almost 700 clients, including well-known companies like ITC Ltd., Ruchi Soya Ltd., Louis Dreyfus, Allana Group, and more [26].

Shri Mahavir Agritech keeps an annual supply of 850,000 wheat sacks on an annual basis, while exporting its wheat products to 85 countries worldwide, mainly through its client Allana Group, one of the major exporters of the country . These three markets are taken into account in this case study: Asia, Africa and Middle East, with sales prices averaging \$24.42, \$28.11 and \$31.43 per wheat sack respectively [27]. The planning horizon spans a total of 12 months. In India, wheat is collected in March, April, May, and June. These months make up our hypothetical base harvest period. The states of Haryana, Punjab, Rajasthan, Uttar Pradesh, West Bengal, Madhya Pradesh, Gujarat, Maharashtra, Tamil Nadu, Andhra Pradesh, and Bihar are the ones that produce the most wheat, comprising the agri-food production cluster in this case . Supply upper-bounds are shown in Table 1 for the basic event ψ_0 and risk acceptance approach r_0 respectively. Even if all wheat kinds are combined into a single product, the commodity is differentiated by the sources of its supply and the timing of its harvest. The case study is a multi-commodity model as a result. The author considers two supply locations, Uttar Pradesh , UP (S1) and other Indian suppliers (S2).

Table 1 Supply upper-bound (thousands of sacks)
Source: Author's calculations & compilation

Supply location	Commodity	Risk management	March	April	May	June
y	$c = (y, e, \hat{t})$	Strategies r	t=3	t=4	t=5	t=6
1	(1 ,1 ,3)	$\forall r \in \xi \backslash \{SD\}$	227	0	0	0
1	(1 ,1 ,4)	$\forall r \in \xi \backslash \{SD\}$	0	227	0	0
1	(1 ,1 ,5)	$\forall r \in \xi \backslash \{SD\}$	0	0	67	0
1	(1 ,1 ,6)	$\forall r \in \xi \backslash \{SD\}$	0	0	0	38
2	(2 ,1 ,3)	$\forall r \in \xi$	56	0	0	0
2	(2 ,1 ,4)	$\forall r \in \xi$	0	56	0	0
2	(2 ,1 ,5)	$\forall r \in \xi$	0	0	18	0
2	(2 ,1 ,6)	$\forall r \in \xi$	0	0	0	7

Moreover, in Table 2, data for demand upper-bounds are estimated.

Table 2 Demand upper-bound (thousands of sacks), Source: Author's calculations & compilation

Demand location	Product	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
z	e	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10	t=11	t=12
1	1	61	61	61	61	61	58	58	43	43	43	43	43
2	1	56	56	56	56	27	27	27	14	14	14	7	7
3	1	58	58	58	58	57	33	33	18	18	14	14	14

Estimated lead times and sack prices for transport are shown in Table 3.

Table 3 Supply to market shipping lead-time and costs
Source: Author's calculations & compilation

Supply location y	Demand location z		
	1	2	3
1	2 ($3.23)	1 ($3.11)	1 ($3.11)
2	2 ($3.23)	1 ($3.11)	1 ($3.11)
3	2 ($3.23)	1 ($3.11)	1 ($3.11)

Supply costs paid to growers and inventory holding cost characteristics are shown in Table 4.

Table 4 Purchase cost ($ per sack) and inventory storage cost
Source: Author's calculations & compilation

Variable	Location	Value
Supply cost $s^{\kappa}(y,c,t,\rho_0)$	∀y=1,2	$4.23
Supply cost $s^{\kappa}(y,c,t,\rho_0)$	∀y=3	$4.05
Supply side inventory storage cost $s^{m}(y,c,t)$	∀y=1,2	$3.11
Supply side inventory storage cost $s^{m}(y,c,t)$	∀y=3	$3.04
Demand side inventory storage cost $s^{m}(z,c,t)$	∀z∈ Z	$4.05

During 2022, India experienced the warmest March in 122 years, which led to a low yield of wheat [28]. The harvest in UP (S1) is delayed by a month in the author's extreme weather disruption event, but the yield is unaffected. The likelihood of a disruption is 30%. On the other hand, the likelihood of the basic event is 70%. Shri Mahavir Agritech is concerned about this disruptive event since any delay in getting new season wheat into its key markets results in significant revenue losses. The author makes the fixed cost assumption that it will cost $14 million to implement an approach for moderating disruption probability in order to minimize the likelihood of a significant weather disruption by 10%. The author marks the particular realization during considerable weather disturbance with r= 〖SCRMP〗 ^M.

On Friday, May 13, 2022, the Indian government imposed a restriction on wheat exports, citing worries about India's food security raised by the sudden rise in global wheat prices. Exemptions had been granted for shipments to other countries that the government had authorized in order to meet those countries' obligations for food security after receiving requests from those governments, as well as export agreements with customs registration or an irrevocable letter of credit on or before May 13, 2022. The Government of India's capacity to distribute wheat under its domestic food assistance/security programs was impacted by the lower-than-anticipated 2022 wheat harvest, rising food inflation, and low government acquisition of wheat under its Minimum Support Price program [29].

According to the author, a disruption at the UP (S1) caused by a ban on exports would cause an output reduction of 70% in either March or April. Since most of the wheat is harvested during these two months, and since UP serves as its main source of supplies, these two eventualities worry Shri Mahavir Agritech the most. The likelihoods of the base event and two disruption events involving ban on exports are 50% (base), 25%, and 25% respectively. The worst-case event would involve a ban on exports in March, which would have a bigger negative effect on financial performance. The chance of ban on exports disruption in March and April would be decreased by 5% (from 25% to 20%) and 20% (from 25% to 5%) respectively, by using supply chain risk management plans (SCRMP). However, a fixed cost of $3M is anticipated to accompany the implementation of the approach. The author designates the precise realization subject to ban on exports disruption as r= 〖SCRMP〗 ^H.

The most important distributor of Shri Mahavir Agritech in the USA is Parmar Dhanraj Inc. based in Hayward, California, serving the entire West Coast of USA. The fixed cost of reserving an extra backup supply of ten million sacks from California in March is projected to be $7 million if the author employs the backup suppliers method (r=BS). Moreover, the author replaces five million sacks from the UP supply with the Californian source as part of the supply diversification plan (r=SD). Instead of a fixed cost, this approach has an additional variable cost of $3.67 each sack. The costs are increased for the BS=BS∩SD joint approach.

4.2 Model evaluation and risk mitigation strategies

Since the author has used Python-MIP before, that allows the development of improved Branch-&-Cut algorithms, he uses Python-PuLP which is a high-level modeling package that makes the most of its potential by letting users write programs using expressions that are native to the language and, if possible, avoiding extra syntax and keywords. This software has been used to solve this study's case problem. The predicted earnings and the worst-case (extreme weather disruption) profits for various risk management approaches are shown in Table 5.

Table 5 Outcomes of efficiency enhancement under extreme weather disruption
Source: Author's calculations & compilation, Note: EAT is short for Earnings After Taxes

Offered approach	Estimated EAT (in $mn.)	Enhanced efficiency (%)	Worst EAT (in $mn.)	Enhanced efficiency (%)
No approach	174,35	n/a	166,53	n/a
SD, BS, $SCRMP^M$	181,54	4,12	175,47	5,37
SD, $SCRMP^M$	179,41	2,90	168,21	1,01
SD, BS	177,85	2,01	175,47	5,37
BS, $SCRMP^M$	177,14	1,60	174,23	4,62
$SCRMP^M$	176,46	1,21	166,53	0,00
SD	176,39	1,17	168,21	1,01
BS	176,12	1,02	174,23	4,62

In the first cost settings, a risk acceptance method serves as a baseline for comparison. To accomplish the largest enhancement in the predicted profit, all strong and resilient approaches are used in the ideal solution. The result of combining all three approaches is an enhancement of 4.12%. 2.90% represents the best enhancement over subsets of two approaches. The r= 〖SCRMP〗 ^M yields the best results when only one option is available (either BS, SD, or 〖SCRMP〗 ^M), although the gains from the other two approaches are close (1.21% versus 1.17% and 1.02%). When all three (or both BS, SD) approaches are employed, the best profit increase is 5.37% in the worst-case event. The 〖SCRMP〗 ^(M)does not have an impact on the worst-case event because it only influences the likelihood of the disruption event and not the profit when the event occurs.

As observed, while there is some replaceability between the approaches, the significance is rather small (the enhancement of the joint approaches is lower than the total of the individual enhancements). That is, by putting the approaches into practice simultaneously, a sizable benefit can be realized. Approaches BS, SD exhibit the least substitution loss, whilst BS, 〖SCRMP〗 ^(M) exhibit the most. As a result, it is rather biased to draw a broad conclusion on the substitution impacts of solid against sustainable approaches.

The outcomes for the ban on wheat exports disruption are displayed in Table 6. In contrast to an extreme weather disruption, implementing the two approaches of BS and SD is nearly as effective as implementing all three approaches (2.80% vs. 2.88%).

Table 6 Outcomes of efficiency enhancement under ban on wheat exports disruption
Source: Author's calculations & compilation, Note: EAT is short for Earnings After Taxes

Offered approach	Estimated EAT (in $mn.)	Enhanced efficiency (%)	Worst EAT (in $mn.)	Enhanced efficiency (%)
No approach	180,12	n/a	175,46	n/a
SD, BS, $SCRMP^H$	185,31	2,88	185,27	5,59
SD, $SCRMP^H$	184,11	2,22	178,69	1,84
SD, BS	185,17	2,80	185,27	5,59
BS, $SCRMP^H$	181,54	0,79	182,81	4,19
$SCRMP^H$	181,45	0,74	175,46	0,00
SD	182,16	1,13	182,42	3,97
BS	181,51	0,77	182,81	4,19

The 〖SCRMP〗 ^(H)approach is therefore ineffective, despite its $3 million relatively modest cost. Additionally, when just one approach is permitted, SD is twice as effective as BS under yield disruption (1.13% versus 0.77% profit enhancement). However, both SD and BS perform similarly when extreme weather occurs (profit enhancement of 1.17% vs. 1.02%). Similar to Table 5, there is some degree of replaceability between the approaches, although the magnitude is still quite small. Again, approaches BS and SD exhibit the lowest replaceability loss, while approach BS with approach 〖SCRMP〗 ^(M)exhibits a sizable replaceability loss.

5 Conclusions

The world has been made aware of the interdependence of nations' basic food supplies thanks to COVID and related initiatives, the dangers of lean supply chains, where inventories are reduced or eliminated, and the susceptibility of this global agrifood supply chain architecture to disruptions. The environmental impact of these worldwide agrifood supply chains as well as the environmental impact of the average person's diet are both being questioned by the present climate change agenda, which is being implemented by various governments.

Some governments, such as the Netherlands, have begun purchasing farmland from farmers to reduce farming activities and, as a result, the country's agri-food production after identifying farmers as the biggest contributors to climate change. Mega food production hubs are spreading environmental effect (and contributing to climate change) to the countries that import food from them. The allocation of resources may be preferable from the perspectives of efficiency and the environment at large, but for the major agri-food production hubs that are now located in the Americas and Europe, this strategy is not advantageous at the national level under the current calculating methodology.

By creating a two-stage stochastic programming model, this study attempts to propose robust and resilient risk management approaches in the supply chain of agricultural foods. The model is used in a case study of Shri Mahavir Agritech wheat supply chain to examine how well a number of strong and adaptable solutions work when faced with risks related to extreme weather and ban on exports disruptions. The modeling outcomes and conclusions provide crucial managerial insights into a number of overarching supply chain risk management principles.

As further research, the author believes that new KPIs like the amount of time containers spend in ports (dwell time) should be introduced in this study's model. The 2021–22 supply chain crisis' lingering effects, the implications of Russia's invasion of Ukraine on logistics in Europe, the acceleration of wealthier economies in port productivity, and the digitalization of end–to–end supply chains all contribute to the fact that emerging economies typically experience shorter delays than industrialized economies. Middle-income nations could outperform both their peers and more developed nations if they exhibit consistent performance across all supply chain components [30,31]. Moreover, agri-food production self-sufficiency at the national level will be a significant KPI; in other words, the extent to which the nation can provide for the requirements of its own people through domestic farming, including, of course, foreign tourists, despite potentially greater expenses. Over the past 50 years, many countries' levels of self-sufficiency have declined as a result of the existence of large-scale international agri-food production hubs [32].

Eventually, a limitation of the current study is the absence of any environmentally sustainable logistics options; options for logistics that are environmentally friendly can reduce supply networks' carbon footprints while facilitating trade. Environmentally sound decisions include switching to fewer carbon-intensive freight modes, warehousing that uses less energy, or employing more of the available capacity. Furthermore, price unpredictability is outside the purview of this study. Despite the fact that price unpredictability is important in some other supply chain problem settings, in the current instance that include a supply chain for premium fresh produce, price is taken into consideration as an established component and no price promotion is recommended; as a result, if product quality declines below the desired level, products are disposed of. Additionally, market capabilities for premium goods are typically higher than supply, reducing the possibility of a drop in demand.

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Prioritizing design for recycling criteria in Moroccan manufacturing

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Abstract: This study investigates the prioritization of Design for Recycling (DfR) criteria within Moroccan manufacturing Micro, Small, and Medium-sized Enterprises (MSMEs). Despite the potential of MSMEs to drive sustainable practices, a comprehensive understanding of key DfR criteria and their prioritization remains limited, particularly in emerging economies. These enterprises, often characterized by their adaptability and resource efficiency focus, are uniquely positioned to adopt sustainable practices like DfR. However, MSMEs, particularly in Morocco, face challenges in integrating DfR principles effectively. This is often due to a lack of awareness and understanding regarding key DfR criteria and how to prioritize them within their specific operational context. To address this gap, a context-specific, multi-level DfR criteria framework is developed, tailored for Moroccan manufacturing MSMEs. The Best-Worst Method (BWM), a robust multi-criteria decision-making technique, is employed to prioritize these criteria within a sample of eight Moroccan manufacturing MSMEs. Our findings reveal that materials compatibility and the use of recycled materials are paramount for optimizing recyclability. This prioritization is influenced by the unique challenges and opportunities within the Moroccan context, including limited recycling infrastructure and a reliance on informal recycling practices. This research provides practical guidance for Moroccan MSMEs seeking to integrate DfR principles into their design processes, contributing to sustainable manufacturing practices. Moreover, it establishes a methodological and theoretical foundation for future research on DfR implementation in emerging economies.

1 Introduction

Micro, small, and medium-sized enterprises (MSMEs) play a crucial role in driving economic growth, particularly in emerging economies [1]. Their inherent adaptability and resource efficiency make them well suited to embrace sustainable practices, such as Design for Recycling (DfR). However, integrating DfR principles into design processes can be challenging for MSMEs [2].

While DfR is a cornerstone of eco-design, much of the existing research focuses on theoretical frameworks or general principles [3-11]. This leaves MSMEs with limited actionable guidance for practical implementation. Moreover, there is a lack of understanding regarding the specific DfR criteria most crucial for these enterprises. This is particularly true in emerging economies like Morocco, where manufacturers must navigate a unique recycling landscape characterized by informal practices and infrastructural limitations.

This study addresses these gaps by developing and validating a context-specific framework of DfR criteria tailored to the needs of Moroccan manufacturing MSMEs. Drawing from existing literature and expert consultations, we meticulously assess and prioritize these criteria using the Best-Worst Method [12], a robust multi-criteria decision-making technique. This approach offers a practical roadmap for MSMEs seeking to enhance product recyclability in the design phase, thereby contributing to sustainable manufacturing practices. Additionally, our research provides a foundation for future investigations into DfR implementation across various contexts. The study has three primary objectives:

- Identify DfR criteria: Develop a comprehensive DfR decision framework tailored for manufacturing sectors.
- Assign weights to DfR criteria: Determine the relative significance (weights) of DfR criteria within the manufacturing context.
- Explore implications: Investigate the managerial, practical, and country-specific implications of this research.

To achieve these objectives, we conducted a comprehensive literature review on DfR and eco-design, extracting and synthesizing key criteria to form the foundation of our framework. This framework was further refined and validated through consultations with experts and practitioners. We then employed the BWM tool to evaluate the framework across eight Moroccan manufacturing firms, enabling us to prioritize the criteria and establish a strategic implementation pathway.

This paper makes several significant contributions to the field of DfR and sustainable manufacturing:

- Comprehensive framework: It develops a comprehensive, multi-level DfR criteria framework specifically tailored for manufacturing contexts. This framework offers a systematic decision-making tool, guiding practitioners in effectively integrating DfR principles into their product design processes.
- Methodological advancement: The study employs a novel application of the BWM, a robust multi-criteria decision-making technique, to assess and prioritize DfR criteria. This approach provides a rigorous, data-driven method for prioritizing DfR factors based on their relative importance.
- Empirical Insights: The research applies the proposed framework and methodology within the Moroccan manufacturing sector, revealing challenges and opportunities for MSMEs adopting DfR, improving understanding of sustainable manufacturing practices in this context.

This paper is organized as follows: Section 2 explores existing research on design for recycling criteria. Section 3 introduces the methodology and framework. Section 4 applies the framework to a real-world scenario. Section 5 analyzes the results. Section 6 concludes the paper.

2 Analysis of design for recycling criteria: a comprehensive review

2.1 Design for recycling

Growing environmental concern in the 1990s prompted a fundamental shift in product design, emphasizing the minimization of ecological impact. This shift is underscored by a 2021 European Commission report, which emphasizes the significant influence of the design phase on a product's environmental footprint [13]. Eco-design has emerged as a key solution, integrating environmental considerations throughout the entire product lifecycle. Its primary objective is to minimize environmental impacts without compromising performance or economic viability [14]. Design for Recycling is a critical pillar of eco-design, strategically addressing the product's end-of-life to facilitate material recovery and promote closed-loop systems. By optimizing products for recycling, DfR contributes to the broader objectives of a circular economy [15].

Guided by eco-design principles, which are aligned with waste management hierarchies such as the EU's Waste Framework Directive [16], manufacturers are increasingly integrating environmental considerations into their decision-making [14]. Eco-design emphasizes a preventative approach, prioritizing waste prevention, reuse, recycling, and resource recovery. DfR is a cornerstone strategy within this framework, optimizing products for recyclability from the design phase and promoting the use of recycled materials [17].

DfR has become a prominent research area within sustainability, with significant advancements in methodologies and tools empowering designers. Computer-aided tools now enable comprehensive assessments of material recyclability [18,19] and simulate end-of-life (EoL) scenarios to inform design choices [20,21]. Core DfR principles, such as material selection, disassembly considerations, and EoL strategies [15,22,23], are continually adapted to address sector-specific challenges. This is evident in research on the automotive industry [9], the packaging industry [7,24,25], and the emerging field of e-textiles [15], where waste prevention strategies are prioritized due to product complexity.

The recovery of critical raw materials (CRMs) is a vital aspect of DfR. Designers must integrate disassembly techniques and utilize specialized indices [26] to facilitate CRM extraction. However, research highlights systemic barriers that hinder DfR implementation, including limitations in recycling infrastructure, inadequate policy incentives, and fragmented stakeholder collaboration [2,6,11,25,27]. To fully realize the potential of DfR driving the transition to a circular economy, a deeper understanding of design criteria is crucial. This includes material selection, product architecture, EoL scenarios, and their interplay with existing recycling infrastructure and policy frameworks.

2.2 Review of design for recycling criteria

Design for Recycling (DfR) has garnered significant attention within the research community [17,18,20,27,28]. While core DfR principles, such as product architecture, material selection, and end-of-life considerations, are undeniably important, their practical effectiveness depends on contextual factors. Product characteristics, technological limitations, and recycling infrastructure all influence how DfR criteria should be prioritized [5,19,25,29].

A product's architecture significantly influences its recyclability. Simplicity, achieved by minimizing complexity and fastener use, facilitates disassembly [2,9,15,23,27]. Modularity, where products are composed of easily separable modules, facilitates targeted recycling of individual material streams [8,15,27]. Designing for disassembly ensures ease of access to components through non-permanent connections, preserving material integrity [11,18,26]. Standardizing parts and fasteners allows for the use of common disassembly tools, streamlining recycling procedures [7,11,18,20,21].

Material selection significantly influences the efficacy of DfR strategies. Choosing materials with well-established recycling pathways promotes efficient resource recovery [9,24]. Incorporating alternative materials like bioplastics, wood, or other sustainable options can offer environmental benefits [11,15]. When using multiple materials, ensuring compatibility is critical to avoid complications during recycling [2,3,8,18,19]. Using recycled content, where quality and performance allow, contributes to closed-loop material systems within a circular economy [4,23,27,30]. Minimizing or eliminating contaminants and hazardous substances is essential to avoid challenges within recycling systems [2,22,25]. Limiting material diversity and simplifying material choices improve a product's recyclability potential [9,11]. Market factors, such as the economic feasibility of using recycled materials, can also influence material selection decisions [2,28].

Proactive consideration of EoL scenarios is fundamental to DfR. Implementing standardized labelling systems for materials, fasteners, and components promotes efficient sorting and assessment within recycling facilities [2,24,26,27,30]. Aligning product designs with existing recycling systems and technologies optimizes resource recovery [2,5,18]. Adhering to current and anticipated recycling regulations is critical [6,25]. Providing clear information on disassembly, composition, and recyclability to end users and recyclers facilitates product recyclability at the EoL stage [21,28].

This review identifies core DfR criteria, which are interdependent and should be addressed holistically throughout the design process [22,27]. Based on an extensive literature review and discussions with industry professionals, this research proposes a three-dimensional DfR framework encompassing product architecture, material considerations, and EoL considerations. For ease of application, these dimensions are further divided into 14 sub-criteria, detailed in Table 1.

2.3 *Research gaps and highlights*

Existing research provides a valuable foundation for understanding DfR criteria, encompassing material selection [2], implementation frameworks [5,23], and tools for recyclability assessment [18,22,29]. However, a critical gap exists in empirically prioritizing these criteria within real-world manufacturing contexts, particularly in emerging economies. The lack of data driven weighting of individual criteria hinders designers seeking to optimize product recyclability from the outset.

Research suggests that existing DfR theories and conceptual models often are often difficult to apply directly to Micro, Small, and Medium-sized Enterprises (MSMEs) [2]. Considering the dominance of MSMEs in Morocco's economic landscape [31] and the intensifying pressure of global environmental regulations, proactive green design initiatives across all industry scales.

This study addresses these gaps by conducting a systematic survey of Moroccan manufacturing sector experts to prioritize DfR criteria, focusing on three key areas: product architecture, material considerations, and end-of-life considerations. The Best-Worst Method (BWM) will be used to establish a robust ranking of these criteria, revealing those most critical for designing products with optimized recyclability. This research offers a unique contribution by highlighting the specific challenges and potential solutions relevant to emerging economies. In these contexts, factors such as informal recycling practices and infrastructural limitations [25] must be integrated into early-stage design processes.

2.4 *Development of the design for recycling criteria framework*

This section outlines the two-stage development of a comprehensive Design for Recycling (DfR) criteria framework for the Moroccan manufacturing sector.

- Initial criteria identification: A thorough literature review of existing DfR studies was conducted, resulting in a preliminary list of 27 criteria.
- Criteria refinement and categorization: To ensure practical applicability, industry managers evaluated the initial list, suggesting omissions or redundancies. This feedback resulted in a final selection of 14 essential DfR criteria. Subsequently, through iterative discussions, the managers categorized these criteria into three main categories based on thematic similarities. The final sub-criteria categorization is presented in Table 1.

Table 1 Design for recycling (DfR) criteria and supporting literature

Main Criteria	**Sub-Criteria**	**Short description**	**References**
Product Architecture	Simple Design	Simplify design and use fewer fasteners.	[2,4,7,9,11,15,23,24,27]
	Modular architecture	Design modular products for targeted recycling.	[2,6,8,20,23,27,29,30]
	Design for Disassembly	Design for easy disassembly using accessible components and non-permanent connections	[2,3,6-9,11,15,18-20,23-27,29,30]
	Standardisation	Standardize parts and fasteners to streamline disassembly.	[3,7,18,20,21,23,28,29]
Material Consideration	Use of Recycled Materials	Prioritize recyclable materials with established recycling processes and high recycled content.	[2,4-11,15,19,20,23-30]
	Alternative Materials	Explore sustainable material alternatives.	[11,15,24]
	Materials Compatibility	Use compatible materials in mixed-material products.	[2,3,6-9,18,19,24,26-29]
	Avoid Contaminants	Minimize contaminants and hazardous substances.	[2-4,6-9,15,18,22-27,29]
	Materials Diversity	Simplify material selection by reducing the variety of materials used.	[3,5,7-9,11,15,18,23,25,27,28]
	Economic Convenience of Recycled Material	Evaluate the cost-effectiveness of recycled materials.	[3,4,6,19,21,24,25,28]

End of Life Considerations	Identification and Labelling	Standardize labelling for materials and components.	[2,6-8,11,20,23,26,27,29,30]
	Recycling systems Consideration	Design adaptable products for evolving recycling technologies.	[2,5,6,7,11,19,21,24,29,30]
	Legislative Considerations	Comply with current and future recycling regulations.	[6,25,27]
	Information communication	Provide clear product information for end-of-life management.	[2,21,27,30]

3 Prioritizing DfR criteria: a best-worst method approach

Table 1 highlights the complex, multi-criteria nature of Design for Recycling, with each criterion encompassing various factors that demand careful consideration. Effectively evaluating and prioritizing these criteria is challenging due to their inherent complexity and the potential for inconsistencies in traditional Multi-Criteria Decision-Making (MCDM) methods that rely heavily on pairwise comparisons [32].

To address these limitations and ensure reliable outcomes, this study adopts the Best-Worst Method (BWM) [12]. BWM offers distinct advantages for DfR analysis, making it particularly well-suited for navigating the complexities of this domain:

- Reduced inconsistency: BWM minimizes inconsistencies inherent in traditional pairwise comparisons by focusing on comparisons between the "best" and "worst" criteria relative to all other criteria. This approach provides a more holistic and robust framework, going beyond simply identifying the most efficient alternative. By requiring experts to consider the best and worst criteria as reference points, BWM encourages more deliberate and consistent judgments.
- Streamlined process: BWM utilizes a vector-based approach, streamlining the assessment process and requiring fewer comparisons than matrix-based methods. This reduces the cognitive burden on decision-makers, making it more efficient and less prone to errors, especially when dealing with a large number of DfR criteria.
- Intuitive comparisons: BWM facilitates comparisons against a defined reference (the best and worst criteria), which aligns with intuitive decision-making processes. This makes it a user-friendly tool for practical DfR applications, enhancing the accessibility and understandability of the analysis for both experts and stakeholders.

The selection of BWM for prioritizing DfR criteria stems from its ability to systematically address complex, multifaceted factors while minimizing potential biases. BWM facilitates the structured integration of expert knowledge, which is crucial for understanding the nuances of DfR implementation, particularly within the Moroccan MSME manufacturing context. While expert evaluations may involve some subjectivity, BWM's emphasis on consistency, coupled with a diverse expert panel, mitigates biases and strengthens the credibility of the findings.

Furthermore, this confidence is further bolstered by the successful application of BWM in various real-world applications, including optimizing freight transportation [33], supplier selection [34], and evaluating risk in business continuity [35]. This diverse applicability underscores BWM's value as a robust and adaptable MCDM method across different industries.

The Best-Worst Method (BWM) involves a series of steps to identify the weights of criteria in a MCDM process.

Step 1. Identify Decision Criteria.
Identify the decision criteria $\{C_1, C_2, \dots, C_n\}$ used to evaluate alternatives. These criteria will form the basis for making comparisons.

Step 2. Identify Best and Worst Criteria.
Select the most significant (best) and least significant (worst) DfR criteria from the identified set. This selection focuses solely on the relative significance of each criterion, independent of their specific values.

Step 3. Define Best-to-Others Preferences.
Pairwise comparisons are conducted employing a 9-point scale (1 = equal preference, 9 = extreme preference). These comparisons establish the best-to-others vector (BO) for the most significant (best) criterion, denoted as (1):

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn}) \quad (1)$$

Here, a_{Bj} represents the preference of the best criterion B over criterion j, and $a_{BB} = 1$ (indicating equal preference for the best criterion itself).

Step 4. Define Others-to-Worst Preferences.
Similarly, using the same scale, determine the significance of each criterion over the least significant (worst) criterion. This information is captured in the others-to-worst vector (OW), denoted as (2):

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T \quad (2)$$

Here, a_{jW} represents the preference of criterion j over the worst criterion W, and $a_{WW} = 1$ (indicating equal preference for the worst criterion itself).

Step 5. Calculate weights.

BWM employs an optimization model to calculate the weights of each criterion (w_1^*, w_2^*, ..., w_n^*) This model minimizes the maximum absolute difference between two sets of comparisons $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$.

A minimax model is formulated to achieve this minimization (3).

$$\min \max_j \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\} \quad (3)$$

Subject to,

$\sum_j w_j = 1 \qquad w_j \geq 0$, for all j

Model (3) can be solved by transforming it into the subsequent linear programming formulation (4):

$$\text{Min } \xi^L \quad (4)$$

Subject to,

$|w_B - a_{Bj}w_j| \leq \xi^L$, for all j

$|w_j - a_{jW}w_W| \leq \xi^L$, for all j

$\sum_j w_j = 1 \qquad w_j \geq 0$, for all j

Model (4) being linear and possessing a unique solution implies upon solving it, optimal weights (w_1^*, w_2^*, ..., w_n^*) and an optimal value ξ^L will be derived.

The consistency ratio ξ^{L*} is calculated to indicate the consistency of the comparison system. A Value closer to zero implies higher consistency [12].

4 Practical applications: the case of moroccan MSMEs

4.1 MSMEs in the Moroccan context

MSMEs are recognized for their critical role in driving economic expansion and development in both industrialized and developing nations. They contribute significantly to wealth creation and employment [1]. In Morocco, MSMEs hold a particularly prominent position, constituting nearly 99% of the economic sector [31]. Notably, microenterprises represent the vast majority 88% of all businesses within this sector [31].

Despite their economic importance, MSMEs are significant contributors to global pollution, generating an estimated 60-70% of it [1]. This necessitates the adoption of sustainable practices within the sector. While classification criteria for MSMEs vary by country, Morocco uses a turnover-based system. This system categorizes businesses into microenterprises (annual turnover ≤ 3 million dirhams), very small enterprises (3-10 million dirhams), small enterprises (10-50 million dirhams), medium enterprises (50-175 million dirhams), and large enterprises (> 175 million dirhams). This nuanced approach facilitates targeted support policies for SMEs and allows businesses to assess their growth potential [31].

Despite their substantial environmental footprint, MSMEs often lack comprehensive strategies to address sustainability challenges [1]. This research seeks to address the gap by equipping MSME decision-makers with a robust understanding of DfR criteria. By strategically integrating DfR into their product design process, MSMEs can enhance product recyclability and contribute to broader sustainable manufacturing goals.

4.2 Application of the BWM

To evaluate the practicality of the proposed framework, we engaged in comprehensive discussions with ten experts from eight Moroccan manufacturing MSMEs spanning diverse sectors. These MSMEs were carefully selected to represent a variety of industries. Participants held key positions such as senior design engineer, industrial manager, and product engineer, all of whom play significant roles in the design phase. All participants had at least a decade of operational experience, ensuring a diverse spectrum of perspectives.

Following these discussions, experts from each company participated in a structured evaluation process. Prior to engagement, participants were provided with a briefing outlining the research objectives and detailed clarifications of each criterion. A preliminary refinement phase was conducted, followed by pairwise comparisons using the BWM. Experts identified the most and least important main criteria, which were designated as the "best" and "worst" criteria, respectively. They then compared the "best" criterion against all other criteria, indicating their preferences. Next, they compared all criteria against the "worst" criterion. This process was repeated for the sub-criteria. Individual ratings across all ten experts were aggregated to determine the final rankings of both main and sub-criteria. Table 2 summarizes the identified "best" and "worst" criteria for all ten respondents.

Table 2 Best and worst criteria identified by the respondents

Criterion	"Best" by Respondents	"Worst" by Respondents
Product Architecture (PA)	**2, 7**	**3, 4, 6, 8, 9, 10**
PA1: Simple design	3, 4, 10	5, 8
PA2: Modular architecture	5, 8, 9	2, 6, 7
PA3: Design for disassembly	1, 2, 6, 7	3, 4
PA4: Standardization		1, 9, 10
Material Consideration (MC)	**1, 3, 4, 5, 6, 9, 10**	
MC1: Use of recycled materials	1, 3, 4, 5, 8, 9	
MC2: Alternatives materials		7, 10
MC3: Materials compatibility	2, 6, 7	
MC4: Avoid contaminants	10	
MC5: Materials diversity		1, 3, 4, 5, 8, 9
MC6: Economic convenience		2, 6
End of Life Considerations (EoL)	**8**	**1, 2, 5, 7**
EoL1: Identification and labelling	1, 2, 3, 4, 5, 6, 7, 10	
EoL2: Recycling systems consideration	8	3, 4, 6, 7
EoL3: Legislative consideration	9	1, 2, 5
EoL4: Information and communication		8, 9, 10

The BWM method uses pairwise comparisons to ascertain the relative importance of criteria. To illustrate, Table 3 presents Respondent 1's preferences for the “best” main criterion compared to other main criteria, as well as their preferences for each main criterion compared to the designated “worst” criterion. These pairwise comparisons were conducted using a 9-point scale (detailed in Table 4).

Table 3 present Respondent 1's pairwise comparisons using the Best-Worst Method (BWM). These comparisons establish preferences for the “best” main criterion relative to other main criteria (Best-to-Others vector, or BO), and for each main criterion compared to the “worst” criterion (Others-to-Worst vector, or OW).

Table 3 Pairwise comparison of main criteria by respondent 1

BO	PA	MC	EoL
Most important: Material Consideration (MC)	4	1	8
OW	**Least important: End of Life Considerations (EoL)**		
PA	3		
MC	8		
EoL	1		

For example, in the BO vector (Table 3), the value of 4 at the intersection of Material Considerations (MC) and Product Architecture (PA) signifies that MC is considered “Somewhat to considerably more significant” than PA. The diagonal entries (e.g., MC and MC) are automatically assigned a value of 1, denoting equal importance. Similarly, in the OW vector (Table 3), the value of 8 at the intersection of MC and EoL considerations reflects Respondent 1's judgement that MC is “Highly to exceptionally more significant” than EoL considerations.

Table 4 BWM scale for pairwise comparisons

Term	Scale
Equally significant	1
Equivalent to somewhat more significant	2
Somewhat more significant	3
Somewhat to considerably more significant	4
Considerably more significant	5
Considerably to highly more significant	6
Highly more significant	7
Highly to exceptionally more significant	8
Exceptionally more significant	9

After evaluating of the main criteria, Respondent 1 undertook pairwise comparisons of the sub-criteria within each category using the same 9-point scale (1-9). The results of these comparisons for Product Architecture, Material Considerations, and End-of-Life Considerations are presented in Tables 5-7. Weights for both the main criteria and their associated sub-criteria were then calculated using equation (4). Table 8 summarizes these calculated weights for Respondent 1.

This process of pairwise comparison and weight calculation was repeated for each of the ten respondents. The final weights for the main criteria and sub-criteria were then calculated by averaging the individual weights across all respondents. Table 9 presents these final averaged weights.

Table 5 Pairwise comparison for PA sub-criteria by respondent 1

BO	PA1	PA2	PA3	PA4
Most important: Design for disassembly (PA3)	2	3	1	8
OW	**Least important: Standardization (PA4)**			
PA1	5			
PA2	4			
PA3	8			
PA4	1			

Table 6 Pairwise comparison for MC sub-criteria by respondent 1

BO	MC1	MC2	MC3	MC4	MC5	MC6
Most important: Use of recycled Materials (MC1)	1	6	5	4	8	3
OW	**Least important: Materials diversity (MC5)**					
MC1	8					
MC2	2					
MC3	5					
MC4	6					
MC5	1					
MC6	4					

Table 7 Pairwise comparison for EoL sub-criteria by respondent 1

BO	EoL1	EoL2	EoL3	EoL4
Most important: Identification and labelling (EoL1)	1	2	5	2
OW	**Least important: Legislative consideration (EoL3)**			
EoL1	5			
EoL2	4			
EoL3	1			
EoL4	4			

Table 8 Weights of main and sub-criteria for respondent 1

Main Criteria	Local weights	Sub Criteria	Local weights Sub-criteria	Global Weights	Ranking
PA	0.194	**PA 1**	0.270	0.052	7
		PA 2	0.180	0.035	9
		PA 3	0.494	0.096	4
		PA 4	0.056	0.011	12
MC	0.722	**MC 1**	0.438	0.317	1
		MC 2	0.091	0.066	6
		MC 3	0.110	0.079	5
		MC 4	0.137	0.099	3
		MC 5	0.041	0.030	10
		MC 6	0.183	0.132	2
EoL	0.083	**EoL 1**	0.519	0.043	8
		EoL 2	0.305	0.025	11
		EoL 3	0.053	0.004	14
		EoL 4	0.122	0.010	13

5 Discussion and analysis of results

The substantial weight accorded to material considerations (MC) underscores the paramount importance of material selection in determining a product's recyclability. This aligns with the global emphasis on material-centric DfR practices and the principles of a circular economy. Effectively managing the flow of materials throughout the product lifecycle, from raw material sourcing to end-of-life processing, is crucial for achieving circularity. The high rankings of criteria like “use of recycled materials” (MC1) and “material compatibility” (MC3) further solidify this commitment to optimizing material flows. This emphasis also reflects the realities of the Moroccan recycling industry. Limited infrastructure and dependence on informal sorting necessitate a focus on readily identifiable, compatible materials with established recycled content sources. By prioritizing such materials, Moroccan MSMEs can ensure their products seamlessly integrate into the existing recycling ecosystem.

While product architecture is significant, its lower emphasis compared to material considerations suggests that extensive design overhauls might be constrained within the surveyed companies. These constraints could arise from various factors: limited production capacity, where smaller production runs may not justify investments in complex product architectures; compliance with external market demands, which may impose strict design specifications that limit flexibility; and technological limitations, where existing manufacturing setups may not be easily adaptable to intricate designs. However, the prioritization of “modular architecture” (PA2) and “design for disassembly” (PA3) is noteworthy. This aligns with trends in emerging economies, where customization, faster time-to-market, and easier repairability are increasingly valuable.

This seemingly forward-thinking approach within the Moroccan MSME context could be attributed to market adaptation. Modular designs may be more suitable for smaller production runs or accommodating custom orders, supporting a thriving informal sector of product repair and refurbishment in Morocco. This highlights the role of the informal sector in extending product lifespans. The lower emphasis on extensive product architecture overhauls might contrast with developed economies, where larger manufacturers generally have greater flexibility for design innovation. This difference could be influenced by technological constraints and limited investment capacity of Moroccan MSMEs. Furthermore, the need to adapt their designs to the realities of an informal recycling sector appears particularly important for Moroccan MSMEs.

The relatively lower weight given to “recycling systems consideration” (EoL2) and “legislative considerations” (EoL3) indicates that MSMEs perceive limited influence over these broader life cycle aspects. This underscores the need for collaborative initiatives between stakeholders to optimize the reverse logistics processes associated with DfR. This includes:

- Manufacturers: Implementing DfR principles to facilitate efficient sorting and processing within the reverse logistics flow.
- Policymakers: Establishing clear regulations and developing recycling infrastructure.
- Recycling industry: Investing in sorting technologies and fostering formal recycling channels.

Such collaborative efforts should prioritise infrastructure enhancement by upgrading sorting and processing facilities to handle a wider range of materials, standardised labelling by implementing clear and consistent labelling systems to guide consumers and recycling operators, and incentivising responsible practices by establishing financial or regulatory incentives to encourage eco-friendly design and responsible consumer behaviour.

The emphasis on material considerations aligns with global trends. However, Moroccan MSMEs demonstrate a unique approach to DfR, focusing on adapting to the limitations of the existing recycling infrastructure and prioritizing materials that readily integrate into this system.

Additionally, the prioritization of "Modular Architecture" (PA2) and "Design for Disassembly" (PA3) within the constraints of production capacity suggests a strategic approach that balances practicality with potential benefits for repairability and market adaptation. Further comparative studies exploring DfR priorities across MSMEs in developed and emerging economies would provide valuable insights into how economic context, supply chain dynamics and recycling infrastructure influence these priorities.

Table 9 Aggregate weights of DfR criteria for all the respondents

Main Criteria	Local weights	Sub Criteria	Local weights Sub-criteria	Global Weights	Ranking
PA	0.237	PA 1	0.275	0.065	8
		PA 2	0.294	0.070	7
		PA 3	0.294	0.070	6
		PA 4	0.137	0.032	13
MC	0.539	MC 1	0.298	0.161	1
		MC 2	0.118	0.064	9
		MC 3	0.198	0.107	2
		MC 4	0.169	0.091	4
		MC 5	0.077	0.042	12
		MC 6	0.140	0.075	5
EoL	0.224	EoL 1	0.459	0.103	3
		EoL 2	0.211	0.047	10
		EoL 3	0.210	0.047	11
		EoL 4	0.120	0.027	14

6 Conclusion and future research

This research contributes to the theory and practice of Design for Recycling (DfR), particularly within the context of Moroccan manufacturing MSMEs. By introducing the Best-Worst Method (BWM) for prioritizing DfR criteria, this study offers a rigorous, data-driven approach applicable across diverse economic contexts. The multi-level DfR framework developed serves as a valuable tool for both researchers and practitioners, enabling structured evaluation and comparison of DfR initiatives. Furthermore, by focusing on the unique context of Moroccan MSMEs, this study addresses a crucial knowledge gap and provides insights into the specific challenges and opportunities these manufacturers face in emerging economies. This nuanced understanding enhances the practical relevance of existing DfR frameworks and underscores the need for globally inclusive approaches to sustainable design.

The prioritized DfR criteria identified offer manufacturers a clear roadmap for implementation. The emphasis on material considerations, such as the use of recycled materials and material compatibility, aligns with the strengths of Morocco's existing recycling infrastructure and provides a strategic pathway for immediate improvements in product recyclability. Additionally, the focus on modular architecture and design for disassembly reflects the specific technological landscape and market demands in Morocco, suggesting proactive strategies for optimizing recyclability within these constraints.

At a national level, this research highlights the potential for developing cross-sector DfR guidance. By combining the proposed framework with sector-specific knowledge, tailored guidelines can be created to address the distinctive challenges faced by various industries within Morocco's manufacturing sector. This study also underscores the need for a comprehensive national dialogue on DfR practices in Morocco. The findings provide a foundation for policy discussions focused on developing robust recycling infrastructure, establishing consistent labeling standards, and incentivizing responsible end-of-life product management.

While this study offers valuable insights, it is essential to acknowledge its limitations. The sample size, while representative of diverse manufacturing sub-sectors and augmented by the inclusion of an engineering consulting firm working with numerous MSMEs, may still limit the generalizability of findings to the broader MSME population in Morocco. Future research with larger and more diverse samples would enhance the generalizability and provide a more comprehensive understanding of DfR prioritization across different MSME contexts. Additionally, applying other MCDM techniques alongside the BWM could further validate the criteria prioritization and offer a more robust analysis.

Further research could delve deeper into the long-term implications of DfR implementation, considering factors such as technological advancements and policy changes. This would involve exploring future trends and potential disruptions that could affect the feasibility and effectiveness of the prioritized DfR criteria. Such an analysis would contribute to a more comprehensive understanding of the long-term implications of DfR strategies and enhance their practical value.

This research paves the way for extensive exploration and implementation of the DfR criteria prioritization framework within Morocco's manufacturing sector. By addressing the identified limitations and fostering interdisciplinary collaboration, future research can further advance sustainable manufacturing practices, benefiting not only Morocco but also contributing valuable insights to the global discourse on DfR in emerging economies.

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Green performance in the Vietnamese water transport industry: a directional distance function with undesirable outputs approach

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Abstract: This study investigates the environmental efficiency and green total factor productivity (GTFP) of the Vietnamese water transport industry. By applying the directional distance function model with undesirable outputs to the annual enterprise census data sample collected by the General Statistics Office of Vietnam, the study estimated the environmental efficiency score and the Malmquist-Luenberger productivity index of the industry for the period from 2015 to 2020. The estimated results from the models show that the average efficiency score of the industry is 37.4%, indicating a low level of environmental efficiency. This implies that the Vietnamese water transport industry has not effectively used resources and technology to minimize negative impacts on the environment. The average GTFP growth reached 2.0% and was mainly contributed by improvements in technical efficiency (2.2%). Meanwhile, the decline in technological change (-0.2%) is the reason for the slowdown in GTFP growth of the industry. The research results also show the difference in efficiency and productivity of the industry when estimated by two approaches of traditional data envelopment analysis and the directional distance function with undesirable outputs.

1 Introduction

Efficiency and productivity analysis aims to evaluate the performance of firms in converting inputs into outputs. Traditional analyses often assume that inputs should be reduced and outputs should be expanded. However, in reality, the production process not only produces desired products or services but it can also create negative impacts such as environmental pollution, waste, or other factors that adversely affect the community and the environment. Ignoring these outputs can lead to an erroneous assessment of the true efficiency and productivity of the production process (Fare et al., 1989; Yang and Pollitt, 2009; Lozano and Gutierrez, 2011) [1-3]. In the case of undesirable outputs, they should be reduced to improve efficiency (Wang et al., 2022) [4]. Economists have recognized the importance of considering unintended outcomes in performance evaluation to promote sustainability and social responsibility of organizations, contributing to building a healthier and more sustainable business environment (Chung et al., 1997; Mahlberg and Sahoo, 2011) [5,6].

The water transport industry plays an important role in economic and trade development of Vietnam. It is not only an efficient mode of transporting goods but also an indispensable part of the global supply chain. As a coastal country with the advantage of a long coastline, close to international shipping routes, there are 3 ports in the list of 50 container ports with the largest throughput in the world (Ho Chi Minh City Port, Hai Phong Port and Cai Mep-Thi Vai Port). The seaport system of Vietnam has received the largest tonnage ships in the world, attracting 40 major international shipping lines to operate. In addition, Vietnam also has a dense river system with 2,360 rivers and canals with a total length of nearly 41,900 km. Along with that are 202 cargo ports, 11 passenger ports, 97 specialized ports and 4,791 inland water wharves. These are advantages for the Vietnamese water transport industry to develop and achieve good operational efficiency (Mai et al., 2023) [7]. However, along with the rapid development of the industry, environmental issues have been becoming increasingly urgent. The use of fossil energy sources and greenhouse gas emissions from water transport activities have contributed to increased environmental pollution and climate change. This poses major challenges for managers and policy makers. The current development trends of the water transport industry are digital technology, green ports, energy conversion, emission reduction and the use of large tonnage ships. These are challenges that require firms to have development plans to adapt promptly.

The issue of environmental efficiency and green total factor productivity (GTFP) growth has garnered the attention of many researchers worldwide. Pioneering studies such as Fare et al. (1989) and Chung et al. (1997) [1,5] proposed the Data Envelopment Analysis (DEA) model with undesirable outputs as an effective method for measuring these concepts. These studies paved the way for analyses of environmental efficiency and GTFP growth in developed economies (Zhang and Choi, 2014) [8], as well as in various industries ranging from energy to manufacturing (Yang and Pollitt, 2009; Li and Lin, 2016) [2,9]. However, this research topic remains relatively new in the fields of maritime transport and coastal ports, with only a handful of studies addressing it. Parris et al. (2023) [10] evaluated and measured the ecological efficiency of 93 largest shipping firms in the world from 2018 to 2022 using the dynamic slack-based non-oriented DEA methodology. Their findings indicate that nations with smaller fleets, such as Canada and Taiwan, achieved higher ecological efficiency due to government sustainability policies. In contrast, tax haven countries like the Marshall Islands, Panama, and Singapore exhibited lower efficiency, as shipping firms in these regions showed less concern for mitigating environmental impacts due to a lack of strict environmental policies. On the other hand, major shipping nations like China have made significant investments in emission reduction through decarbonization strategies and the use of alternative energy sources. The growing emphasis on environmental, social, and governance (ESG) principles among Chinese firms has contributed to improved ecological efficiency. Liu et al. (2023) [11] examined the dynamic development of green growth quality at Chinese coastal ports through the lens of GTFP growth. Using the directional distance function (DDF), the authors estimated the Global Malmquist-Luenberger index following the methodology of Oh (2010) [12] to measure GTFP growth at the ports. Furthermore, the dynamic development of GTFP growth at these ports was explored through kernel density estimation. The results of the study indicated continuous improvement in GTFP growth at coastal ports during the research period. Nevertheless, an issue arises where the inputs for port construction fail to yield efficient outputs, leading to a divergence that shows signs of stabilizing in coastal ports. In the context of Vietnam, a literature review reveals that studies in the water transport industry primarily rely on traditional performance assessment models, without integrating undesirable outputs into productivity growth analyses. This leads to outcomes that do not accurately reflect the actual performance of firms. This represents a significant research gap in terms of environmental efficiency and GTFP growth in the industry, especially as sustainable development has become a critical strategic goal for the country. Thus, this study aims to fill that gap by applying the DEA model with undesirable outputs to measure environmental efficiency and GTFP growth in Vietnamese water transport industry. This approach not only provides a more comprehensive view of the performance of firms but also offers crucial data to help policymakers make informed decisions related to sustainable development, while raising awareness of the role environmental factors play in production activities.

2 Methodology

In the DEA literature, approaches to managing desirable and undesirable outputs are typically classified into three primary methodological frameworks. The first framework involves transforming conventional DEA models such as employing the hyperbolic efficiency measure (Fare et al., 1989) [1], using separate measures for desirable and undesirable outputs (Scheel, 2001) [13], applying a linear monotone decreasing transformation to undesirable outputs (Seiford and Zhu, 2002) [14], and treating undesirable outputs as inputs (Yang and Pollitt, 2009) [2]. The second framework consists of modifications to the slacks-based measure (SBM), as discussed by Tone (2004) and Lozano and Gutierrez (2011) [3,15]. The third framework includes modifications to the DDF, originally proposed by Chung et al. (1997) [5]. Among these, the DDF is particularly prevalent in applications dealing with both desirable and undesirable outputs (Lozano and Gutierrez, 2011; Podinovski and Kuosmanen, 2011) [3,16].

Consider a firm that converts a vector of nonnegative inputs into a vector of nonnegative desirable outputs and a vector of undesirable outputs such as pollution, under the constraints of a fixed technology. Within this production framework, both inputs and desirable outputs are assumed to be strongly disposable, meaning they can increase without affecting the feasibility of the production process. However, undesirable outputs are considered to be weakly disposable, indicating that reducing these outputs is not without cost and will result in a reduction of desirable outputs. Denote the inputs as x, the desirable outputs as y, and the undesirable outputs as u. The production technology described can then be characterized by the technology set P (1), which encompasses all feasible combinations of inputs, desirable outputs, and undesirable outputs.

$$\mathrm{P} = \{(x, y, u) \colon x \text{ can produce } (y, u)\} \tag{1}$$

The radial DDF is defined by Chung et al. (1997) [5] as follows (2):

$$D_r(x, y, u; g) = sup[\beta \colon \{(x, y, u) + \beta g\} \in P] \tag{2}$$

where $g = (g_x, g_y, g_u)$ is a preassigned nonzero vector that specifies the direction in which the distance between the data point (x, y, u) and the production frontier is measured.

The equation (2) presents the most general form of the radial DDF. The distance between the firm and the production frontier can be defined in a specific direction by setting different vectors g. For illustration, we consider three commonly used cases in the literature: $g_1 = (0, y, 0)$, $g_2 = (0,0, -u)$ và $g_3 = (0, y, -u)$.

To estimate technical efficiency using the DDF measure in DEA, one needs to construct a production technology set from observed data. For cross-sectional data consisting of I individuals, the production technology set assuming constant returns to scale (CRS) is constructed as follows (3):

$$P = \{(x, y, u): \sum_{i=1}^{I} \alpha_i x_i \leq x, \sum_{i=1}^{I} \alpha_i y_i \geq y, \sum_{i=1}^{I} \alpha_i u_i = u, \alpha_i \geq 0\} \quad (3)$$

For the case of variable returns to scale (VRS) assumption, condition$\sum_{i=1}^{I} \alpha_i = 1$ is added to the equation (3). Then the equation (3) becomes (4)

$$P = \{(x, y, u): \sum_{i=1}^{I} \alpha_i x_i \leq x, \sum_{i=1}^{I} \alpha_i y_i \geq y, \sum_{i=1}^{I} \alpha_i u_i = u, \sum_{i=1}^{I} \alpha_i = 1, \alpha_i \geq 0\} \quad (4)$$

In the context of panel data, the time-series dimension offers additional insights into the production technology. Economists have proposed various types of production technology sets, including global, window, sequential, biennial, and contemporaneous production technologies. The production technology set at time t is defined as follows (5):

$$P(t) = \{(x, y, u): \sum_{\tau \in \Gamma_t} \sum_{i=1}^{I} \alpha_{i\tau} x_{i\tau} \leq x, \sum_{\tau \in \Gamma_t} \sum_{i=1}^{I} \alpha_{i\tau} y_{i\tau} \geq y, \sum_{\tau \in \Gamma_t} \sum_{i=1}^{I} \alpha_{i\tau} u_{i\tau} = u, \alpha_i \geq 0\} \quad (5)$$

The radial DDF measure for technical inefficiency under the CRS assumption can then be estimated by solving the following linear programming problem (6):

$$D_r(x, y, u; g) = \max_{\beta,\alpha} \beta \quad (6)$$

$$s.t. \sum_{i=1}^{I} \alpha_i x_i \leq x + \beta g_x$$

$$\sum_{i=1}^{I} \alpha_i y_i \geq y + \beta g_y$$

$$\sum_{i=1}^{I} \alpha_i u_i = u + \beta g_u$$

$$\alpha_i \geq 0, i = 1, .., I$$

As for the VRS assumption, condition $\sum_{i=1}^{I} \alpha_i = 1$ is added to the above constraints.

In the equation (6), the constraints on the left-hand side establish the production frontier using the convex hull of the observed data. The right-hand side enables the evaluated firm to modify the inputs (x), desirable outputs (y), and undesirable outputs (u) in the direction of (g_x, g_y, g_u). The DDF aims to maximize the reduction of inputs and undesirable outputs while increasing the desirable outputs, within the parameters defined by the production technology $(x + \beta g_x, y + \beta g_y, u + \beta g_u)$.

The conventional method of assessing productivity change has centered on evaluating the desirable outputs of firms relative to the paid inputs they utilize. This methodology often neglects the production of by-products such as pollution, resulting in potentially biased measures of productivity growth (Chung et al., 1997) [5]. For instance, firms in sectors subject to environmental regulations may find their productivity negatively impacted, as the costs of pollution abatement are included as inputs without accounting for the reduction of pollutants as outputs. To address this, Chung et al. (1997) [5] introduced a productivity index based on the radial DDF measure, known as the Malmquist-Luenberger Productivity Index (MLPI). This index acknowledges both the reduction of undesirable outputs and the increase of desirable outputs. Considering two adjacent periods, labeled s and t, and choosing the direction as $g = (0, y, -u)$, the output-oriented MLPI with undesirable outputs is defined as follows (7):

$$MLPI = \left\{\frac{1+D_r^t(x^s,y^s,u^s;g)}{1+D_r^t(x^t,y^t,u^t;g)} \times \frac{1+D_r^s(x^s,y^s,u^s;g)}{1+D_r^s(x^t,y^t,u^t;g)}\right\}^{1/2} \quad (7)$$

To eliminate the arbitrary selection of base years, a geometric mean of a fraction-based MLPI is calculated using both the base year t and year s. The MLPI indicates productivity improvement when the value exceeds 1, and a decline in productivity when the value is less than 1. According to Chung et al. (1997) [5], the MLPI can be decomposed into two components: one that accounts for technical efficiency change (MLTECH) and another that measures technological change (MLTECCH) (8), (9).

$$MLTECH = \frac{1+D_r^s(x^s,y^s,u^s;g)}{1+D_r^t(x^t,y^t,u^t;g)} \quad (8)$$

$$MLTECCH = \left\{\frac{1+D_r^t(x^s,y^s,u^s;g)}{1+D_r^s(x^t,y^t,u^t;g)} \times \frac{1+D_r^t(x^s,y^s,u^s;g)}{1+D_r^s(x^t,y^t,u^t;g)}\right\}^{1/2} \quad (9)$$

3 Data and variables

The dataset for this study was sourced from the annual enterprise survey data of the General Statistics Office of Vietnam (GSO) covering the period from 2015 to 2020. We exclusively selected data pertaining to water transport firms, specifically those classified under industry code 50 in the Vietnam Standard Industrial Classification (VSIC) system as per Decision 27/2018/QD-TTg by the Prime Minister (VSIC 2018). Firms were excluded if they did not report energy consumption, reported negative numbers of workers, assets, or revenue, or provided incomplete responses. The necessary variables were processed and calculated for each year, after which the data were merged across years using firms' tax codes. This process resulted in a balanced panel dataset of 166 water transport firms over six years (996 observations), including 115 sea and coastal water transport firms (690 observations) and 51 inland water transport firms (306 observations).

In this study, three input variables were used for each firm: capital (K), labor (L), and energy consumption (E). Capital (K), measured in million VND and adjusted to constant prices based on the World Bank's 2010 data, is determined by the average value of total assets at the beginning and end of the year. Labor (L) is calculated as the average number of employees at the beginning and end of the year. Energy consumption (E) involves various energy sources such as electricity, coal, oil, gasoline, and natural gas, each with different technical parameters, complicating the assessment of total energy consumption. To address this, energy consumption is standardized to "Tons of Oil Equivalent - TOE," as specified in Document No. 3505/BCT-KHCN, April 19, 2011, by the Ministry of Industry and Trade. Consequently, E is calculated as the total energy consumption of the firm for the year in "tons of standard TOE".

Regarding output variables, the primary desired output is the value added (VA) of the firm, measured in million VND and adjusted to the World Bank's 2010 constant prices. VA is calculated by summing labor income, fixed asset depreciation, profit before tax, and indirect taxes. CO_2 emissions are considered an undesirable output. Given the lack of detailed CO_2 emission data for each firm in Vietnam, CO_2 emissions from energy consumption were estimated based on the Intergovernmental Panel on Climate Change (IPCC, 2006) [17] guidelines and studies by Chen et al. (2010) and Lan and Minh (2023) [18,19]. Accordingly, the CO_2 emissions are calculated as follows: coal at 2.259 tons CO2 per ton, oil at 3.153 tons CO_2 per ton, natural gas at 2.983 tons CO_2 per 1000 cubic meters, and gasoline at 3.069 tons CO_2 per 1000 liters.

Table 1 Descriptive statistics of input and output variables of the Vietnamese water transport industry in the period 2015-2020

Variables	**Inputs**			**Outputs**	
	L (persons)	**K** (million VND)	**E** (tons)	**VA** (million VND)	**CO_2** (tons)
Mean	74.5507	139539.3	125870.5	21990.78	393539
Std. dev.	142.9181	378527.6	3590005	53526.36	1.12e+07
Min	3	1057	1.408	82.7	3.497938
Max	1246	4823784	1.13e+08	566931	3.53e+08
Skewness	5.091395	7.327462	31.18578	5.343329	31.17702
Kurtosis	34.03907	71.17768	979.5736	39.63687	979.1753

Table 1 presents descriptive statistics of inputs and outputs in the research sample of the Vietnamese water transport industry in the period from 2015 to 2020. During this period, data on input variables show that the average number of employees per firm tends to decrease (-4.82%). The average capital per firm increases by 1.42% per year, but the standard deviation decreases, indicating that the dispersion of investment capital also decreases. The average total energy consumption increases by 7.99% per year and has large fluctuations (average standard deviation of 9.37%). Regarding output variables, the average value added (VA) tends to decrease slightly (-0.17%). The average CO_2 emissions increase by 9.04% with an average standard deviation of 3.38%. We find that there are large fluctuations in energy consumption and CO_2 emissions of firms during the research period. This shows a significant change in production factors and environmental performance of the Vietnamese water transport firms in the period 2015-2020.

4 Results and discussion

By using the equation (6), we calculated the efficiency scores of 166 Vietnamese water transport firms over the period 2015-2020. The estimation procedure in Stata software, created by Wang et al. (2022) [4], was utilized for solving the equation (6). Here, the optimal value β_0 in the equation (6) signifies the inefficiency score. Therefore, a higher β_0 indicates that a particular water transport firm is inefficient or achieves a lower efficiency level. A $\beta_0$value of zezo means that it is impossible to simultaneously expand and contract the desirable and undesirable outputs. Conversely, it suggests that the desirable outputs can be expanded and the undesirable outputs can be contracted whenβ_0 is multiplied by the original values. We also calculate the efficiency scores of the firms using the classical DEA model of Charnes et al. (1978) [20] (CCR), which does not consider the undesirable output, specifically CO_2 emissions. To compare the DDF scores with the CCR scores, the value $(1-\beta_0)/(1+\beta_0)$is used to represent the environmental efficiency of the observed water transport firms. This adjustment reflects the scenario where the desirable output increases by $(1+\beta_0)$times and the undesirable output decreases by$(1-\beta_0)$times the original value. It is important to note that the equation (6), when excluding CO_2 emissions, results in an efficiency score of $1/(1+\beta_0)$, which matches the efficiency score derived from the input-oriented CCR model.

Table 2 Technical efficiency score of the Vietnamese water transport industry in the period 2015-2020

Technical efficiency	**CCR**	**DDF**
Mean	0.687	0.374
Std. dev.	0.131	0.262
Min	0.506	0.011
Max	1.000	1.000

We find that there is a large difference in technical efficiency scores when estimating using both CCR and DDF methods. The estimated results are depicted in Table 2, showing that the technical efficiency scores range from 0.506 to 1.000 on the CCR measure. The average technical efficiency score is 0.687, which means that the overall technical inefficiency under CCR is 31.3%. Our analysis follows input-oriented efficiency measures, so this result implies that inefficient water transport firms can improve their efficiency by reducing their inputs to 31.3% while keeping their outputs unchanged. In contrast, the average technical efficiency score under the DDF measure is only 0.374. We examined the null hypothesis which states that there is no significant difference between the average technical efficiency scores obtained using the CCR method and those derived from the DDF method. The t-test results support the rejection of the null hypothesis at the 1% significance level. This indicates that, on average, the efficiency of the Vietnamese water transport firms varies when considering undesirable outputs, specifically CO_2 emissions.

Table 3 Distribution of environmental efficiency of the Vietnamese water transport industry in the period 2015-2020

Year	**Variable**	**Mean**	**Std. dev.**	**Min**	**Max**
2015	TE_DDF	0.349	0.250	0.049	1.000
2016	TE_DDF	0.399	0.233	0.047	1.000
2017	TE_DDF	0.318	0.270	0.031	1.000
2018	TE_DDF	0.383	0.279	0.011	1.000
2019	TE_DDF	0.331	0.256	0.011	1.000
2020	TE_DDF	0.466	0.257	0.027	1.000

The results of estimating the environmental efficiency score for the Vietnamese water transport industry during the 2015-2020 period, as shown through the TE_DDF variable in Table 3, indicate significant fluctuations and instability, with an average efficiency of only 37.4%. The TE_DDF value reflects technical efficiency while accounting for undesirable outputs, such as CO_2 emissions. The lowest efficiency level was recorded in 2017 at 31.8%, while a marked improvement was observed in 2020, reaching 46.6%, highlighting the industry's ongoing challenges in optimizing technical efficiency and controlling emissions. The expansion of the water fleet to meet growing trade and logistics demand has contributed to increased CO_2 emissions, as most vessels still rely on fossil fuels, particularly diesel. Alternative solutions, such as clean fuels or renewable energy, have not been widely adopted, and the low fuel efficiency of older vessels results in greater emissions and waste compared to modern ships. Additionally, limitations in the Vietnamese seaport system and supporting services for water transport, including a lack of infrastructure for clean fuels and green docking facilities, as well as insufficient policies supporting environmentally friendly transport, continue to undermine the environmental efficiency of the industry and hinder long-term improvements in technical efficiency.

We continue to analyze the environmental efficiency of the Vietnamese water transport sector by three-digit VSIC (sea and coastal transport and inland water transport); by firm size (small-sized, medium-sized and large-sized); and by firm ownership (state and non-state). The estimated results of efficiency scores using the DDF model are shown in Figure 1.

We find that the environmental efficiency scores by sea and coastal transport and inland water transport sectors have significant differences. Specifically, the density of environmental efficiency scores of the sea and coastal transport sector is highest at around 0.2, then gradually decreases and has a second small peak near 1. This shows that there are a large number of firms in this sector achieving low environmental efficiency, but there are also a few firms achieving high environmental efficiency. In contrast, for the inland water transport sector, the density of environmental efficiency scores peaks at around 0.3 and then gradually declines. This density does not have a second small peak near 1 like the sea and coastal transport sector, indicating that fewer firms in this sector achieve higher environmental efficiency. This difference can be explained by the operational characteristics and scale of the two sectors groups. The sea and coastal transport sector is usually larger in scale and has more complex technical requirements, leading to a clear differentiation in environmental efficiency. Meanwhile, the inland water transport sector is usually smaller in scale and has less technical requirements, leading to a higher density concentration at the average efficiency score.

When analyzed by firm size, the results indicate distinct patterns in environmental efficiency among water transport firms. Small-sized firms exhibit the highest density of environmental efficiency scores around 0.2, which gradually decreases, with a secondary peak near 1. This distribution suggests that most small-sized firms have low environmental efficiency, while a few achieve very high efficiency. Medium-sized firms show the highest density of efficiency scores around 0.3, which then gradually

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declines without a secondary peak, indicating a focus on average efficiency. In contrast, large-sized firms display a more widely distributed density of efficiency scores, primarily between 0.2 and 0.4, with a secondary peak near 1. This indicates significant variation in the environmental efficiency of large-sized firms, with some achieving high efficiency and others only average. These differences can be attributed to operational and managerial capacities linked to firm size. Small-sized water transport firms often struggle with optimizing processes and resources, leading to lower environmental efficiency. Conversely, large-scale firms can leverage technology and effective management, though disparities in efficiency remain.

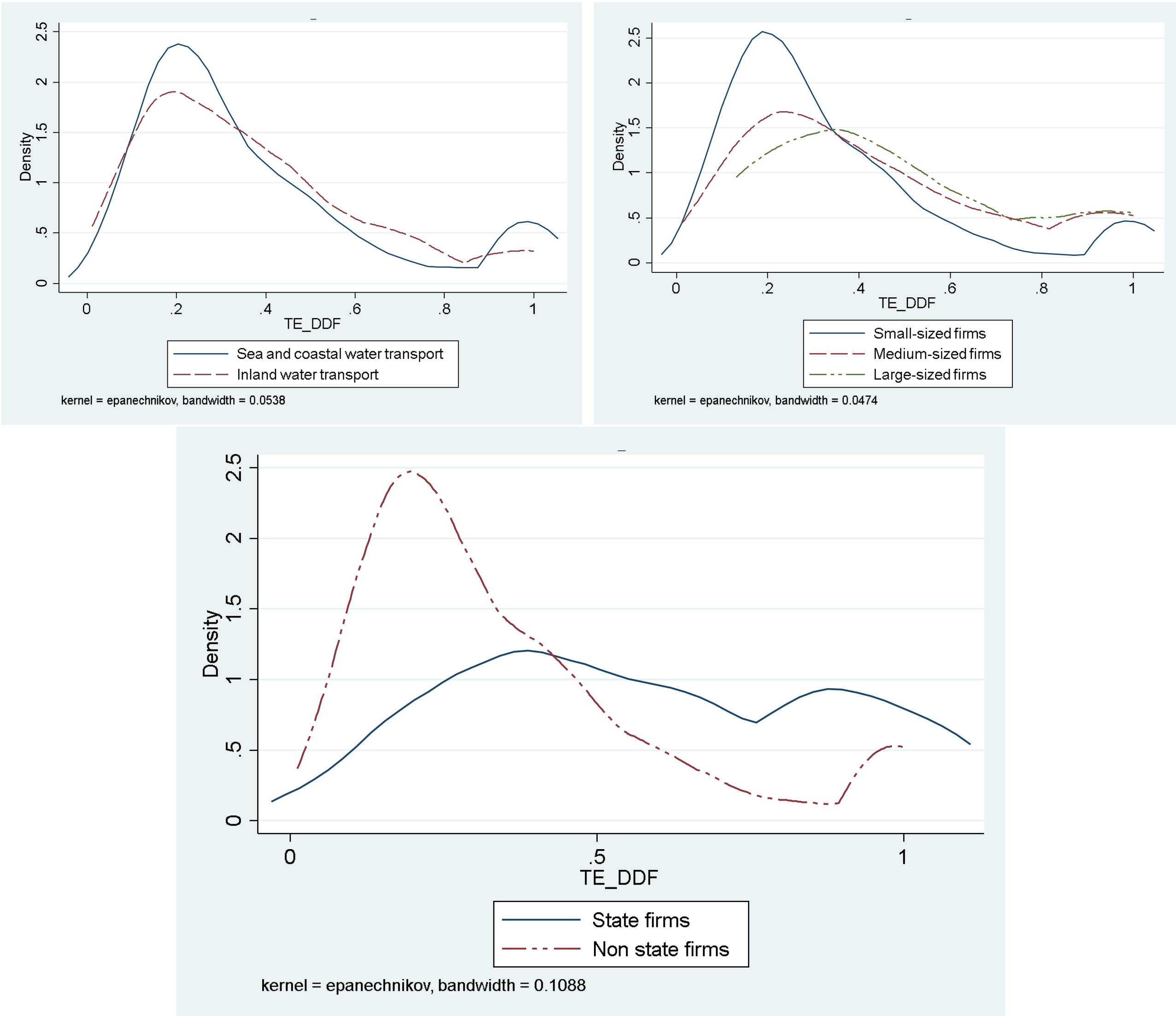

Figure 1 Environmental efficiency of the Vietnamese water transport industry by three-digit VSIC, by firm size and by firm ownership

The analysis of environmental efficiency by firm ownership reveals further differentiation. State firms have a widely distributed density of efficiency scores, concentrated between 0.1 and 0.4, with a secondary peak near 1. This suggests that while many state firms achieve average efficiency, a few attain high efficiency. Non-state firms, however, show the highest concentration of efficiency scores around 0.2, which rapidly decreases without a secondary peak, indicating that most achieve low to average efficiency with few high performers. This divergence can be explained by differences in management, scale, and operational structure. State firms, typically larger and supported by the government, face unique challenges in management and operational efficiency. Non-state firms, despite their flexibility and dynamism, often encounter financial and technological constraints, resulting in lower environmental efficiency.

In summary, the analysis reveals clear disparities in environmental efficiency among water transport firms in Vietnam, based on three-digit VSIC, firm size, and firm ownership. These findings highlight the need for targeted measures to improve environmental efficiency within specific groups of firms.

In the following, based on the DDF specified in the equation (6), we compute the MLPI of the Vietnamese water transport industry by the equation (7) and its components (MLTECH, MLTECCH) by the equations (8) and (9). For comparison, we also calculate the traditional Malmquist productivity index (MPI) by the model of Fare et al. (1994) [21], ignoring the undesirable outputs and decomposing its results by the components of technical efficiency change (MTECH) and technological change (MTECCH). The estimated results are presented in Table 4.

Table 4 Malmquist–Luenberger productivity index of the Vietnamese water transport industry in the period 2015-2020

Year	**Malmquist-Luenberger productivity index**			**Malmquist productivity index**		
	MLPI	MLTECH	MLTECCH	MPI	MTECH	MTECCH
2015-2016	1.001	0.969	1.033	1.002	1.017	0.986
2016-2017	0.987	1.014	0.973	0.933	1.013	0.922
2017-2018	1.031	1.037	0.994	1.011	0.993	1.019
2018-2019	1.027	1.054	0.974	1.038	1.014	1.025
2019-2020	1.051	1.036	1.014	1.026	1.025	1.001
Mean	**1.020**	**1.022**	**0.998**	**1.002**	**1.012**	**0.990**

The traditional Malmquist productivity index estimates show that the Vietnamese water transport industry has seen an average annual productivity growth of 0.2%. Decomposing this index shows that although average efficiency (MTECH) increased by 1.2% during 2015-2020, the decline in technological change (MTECCH) of -1.0% was the source of the total factor productivity drag. Technological progress exhibited negative growth during 2015-2017, and the highest increase in 2018-2019 was 2.5%. Meanwhile, the average annual growth of the MLPI was 2.0%. This average GTFP measure is a combination of the improvement in technical efficiency (MLTECH) of 2.2% and the decline in technological change (MLTECCH) of -0.2%. Overall, we find that the MLPI captures GTFP change, technical efficiency change, and technological change better than the traditional Malmquist productivity index. We also ran a paired two-sample t-test to examine whether the MLPI and the MPI, along with their components, were statistically different. The test results support the rejection of the null hypothesis that the MLPI and the MPI, and their components, are similar at the 5.0% significance level. This suggests that applying the MLPI to the Vietnamese water transport industry provides a different and possibly more accurate view of productivity when considering the undesirable output of CO_2 emissions.

Table 5 Malmquist–Luenberger productivity index of the Vietnamese water transport industry by three-digit VSIC, by firm size and by firm ownership

Malmquist-Luenberger productivity index and its components		**MLPI**	**MLTECH**	**MLTECCH**
By three-digit VSIC	Sea and coastal water transport	1.021	1.031	0.991
	Inland water transport	1.014	1.000	1.014
By firm size	Small-sized firms	1.017	1.019	0.998
	Medium-sized firms	1.021	1.026	0.995
	Large-sized firms	1.048	1.034	1.013
By firm ownership	State firms	1.012	1.012	1.000
	Non state firms	1.020	1.023	0.997

The results of estimating and decomposing the Malmquist-Luenberger total factor productivity index of the Vietnamese water transport industry in the period of 2015-2020 show important trends and characteristics when divided by three-digit VSIC, by firm size, and by firm ownership (Table 5). By three-digit VSIC, the sea and coastal transport sector had a GTFP increase of 2.1%, with the contribution from technical efficiency change (MLTECH) being 3.1%, while technological change (MLTECH) decreased by -0.9%. In contrast, the inland water transport sector had a GTFP increase of 1.4%, in which technical efficiency remained stable and technological change increased by 1.4%. By firm size, small-sized firms had a GTFP increase of 1.7%, in which technical efficiency increased by 1.9% but technological progress decreased slightly by -0.2%. Medium-sized firms saw a 2.1% increase in GTFP, with technical efficiency increasing by 2.6% and technological change decreasing by 0.5%. Large-sized firms had an impressive increase in GTFP (4.8%) as both technical efficiency and technological progress increased by 3.4% and 1.3%, respectively. When divided by firm ownership, state firms saw a 1.2% increase in GTFP, with both technology and technical efficiency remaining stable. Non-state firms saw a 2.0% increase in GTFP, with technical efficiency increasing by 2.3% but technological change decreasing slightly by -0.3%. In summary, the Vietnamese water transport industry has seen positive growth in GTFP during 2015-2020, mainly due to improvements in technical efficiency. However, technological progress remains limited, especially among small and medium-sized firms and non-state firms. Large-sized firms and the inland water transport sector were the groups with the most significant technological improvements during this period.

The above results reflect the fact that the real total factor productivity growth of the industry is overestimated when undesirable outputs are taken into account. This finding is consistent with the results of Chung et al. (1997), Oh (2010), and Li and Lin (2016) [5,9,12]. In these studies, the evaluated firms show more pronounced productivity improvements when using the MLPI, rather than the traditional Malmquist productivity index, in which undesirable outputs are ignored. This suggests that when traditional productivity measures ignore undesirable output changes, they underestimate real productivity growth. The main reason for the underestimation of real productivity growth is that environmental regulations affect the production activities of firms. With environmental regulations, resources must be diverted from producing good outputs to activities that reduce pollution. The traditional Malmquist productivity index does not recognize the positive effects of shifting resources to reduce pollution and assumes that these inputs are inefficient in producing the desirable outputs. However, in practice, the result of these inputs is a reduction in emissions or an improvement in the environment because environmental regulations encourage the adoption of modern pollution-reducing technologies, the transition to less wasteful production processes, and the use of cleaner energy. The traditional Malmquist productivity index does not recognize firms that reduce emissions and therefore underestimates true productivity growth. The findings on GTFP growth of the Vietnamese water transport industry support Porter's hypothesis, which posits that environmental regulations not only do not reduce competitiveness but can also promote competition by encouraging innovation (Porter and van der Linde, 1995) [22].

5 Conclusions and recommendations

The study uses the DDF with undesirable outputs and the MLPI to investigate the environmental efficiency and GTFP growth of the Vietnamese water transport industry from 2015 to 2020. The findings indicate that the environmental efficiency score of the industry remains low during this period, averaging 37.4%, with noticeable fluctuations and variations across different three-digit VSIC codes, firm sizes, and ownership types. Specifically, sea and coastal transport firms, large enterprises, and state-owned firms typically achieve higher environmental efficiency due to economies of scale and government support, although significant disparities exist within each category. Additionally, the research reveals a notable increase in the industry's GTFP growth, averaging 2.0%, with larger firms exhibiting greater overall increases compared to small and medium firms. This suggests that larger firms are more adept at enhancing technical efficiency and adopting technological advancements than small and medium-sized firms. Despite uniform improvements in technical efficiency across the industry, technological progress remains limited, particularly among small and medium-sized firms and non-state firms. This trend highlights that, under stringent environmental regulations, larger firms are more capable of investing in advanced technology and managing resources efficiently, whereas SMEs face greater challenges in achieving technological improvements.

Therefore, to enhance environmental efficiency, increase GTFP, and promote sustainable development in the Vietnamese water transport industry, we propose the following recommendations: Firstly, management agencies should implement policies to support the adoption of technology and emission reduction initiatives by firms. Encouraging firms to adopt green technology will improve environmental performance. Technological advancement should be prioritized in technical and financial support programs, particularly for sea and coastal transport firms, small-sized and medium-sized firms, and non-state firms. Secondly, it is essential to focus on training and skill development programs for workers to optimize production processes within firms. Concurrently, improving management practices is crucial for achieving higher efficiency in the industry. Thirdly, reforming management and enhancing transparency in the operations of state firms is necessary. Promoting cooperation between state and non-state firms to share experiences and technologies can further improve overall efficiency and productivity of the industry. Finally, it is vital to continue advancing environmental regulations that encourage technological innovation and improved production processes, thereby incentivizing the entire industry to enhance environmental efficiency and GTFP. These policies not only help firms meet environmental standards but also enhance the industry's competitiveness in the international market. Furthermore, creating a favorable business environment, combined with appropriate support policies, will enable the Vietnamese water transport industry to develop more sustainably and effectively in the future.

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Innovative solutions for warehouse logistics: improving efficiency with RFID and IoT integration

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Abstract: This research summarises the results of the scientific discussion on the possibilities of improving logistics flow in industrial practice. The objective of the paper is to introduce an exploratory case study aiming at streamlining production logistics flow through the implementation of automatic identification technology (RFID) and new storage solutions in warehouses in industrial enterprises. The main aim of the paper is to introduce an innovative solution regarding implementation of the Internet of Things (IoT) in the warehouse operations to eliminate waste of time and material guided by Plan –Do-Check- Act (PDCA) cycle verified both by observation and statistical methods. The results of this research propose and realise new innovative solutions to reduce waste in logistics processes in warehousing. The key improvements include the elimination of waste and innovative solutions to increase the efficiency of tracking kitting trucks, improving the clarity of the sequencing of kitting carts, and creating standards for the unification of boxes that result in time savings, optimisation of the workplace and scrap minimisation, and increased quality of the logistics processes. The article concludes future recommendations to streamline logistics flow and implement an innovative lean solutions in industrial enterprises.

1 Introduction

Lean logistics is an approach to supply chain and logistics management based on the principles of lean management. Key ideas in lean management include minimising waste, optimising processes, and increasing efficiency. The lean logistics considers possibilities and new solution including Industry 4.0 for minimizing inventory, times, reducing movements, and costs throughout the supply chain, while maintaining the ability to respond quickly to changes in demand and other factors (legislative, economic, ecological, ergonomic and social).

The adoption of lean and green logistics practices brings synergies and improvement to industry [1]. Lean logistic principles, derived from lean manufacturing, are applied throughout the logistics chain, including warehouse and distribution [2]. Essential elements include continuous process improvement, inventory minimisation, and optimisation of material and information flow in logistics [2,3].

Recent studies in scientific papers emphasize elimination of waste in logistics processes, while the emphasis is on the system's contribution, continuous improvement, and enhancement of quality attributes. Several authors [4,5] discussed new opportunities for logistics flow, technical elements in logistics and supply chain management.

Given rapid industrial growth and increasing demands for efficiency, optimising production logistics has become a key concern for many companies. Integration of advanced technologies such as automatic identification systems, including Radio Frequency Identification (RFID), is emerging as a crucial tool to improve the management of warehousing and logistics operations.

Despite numerous studies highlighting the potential of RFID in supply chain management, there remains a notable gap in published contributions addressing its implementation in the specific context of industrial warehouses in the automotive industry. This gap extends to the lack of case studies that combine RFID with new storage solutions and systematically evaluate the results using a continuous improvement methodology.

The objective of the paper is to introduce an exploratory case study aiming at streamlining production logistics flow through the implementation of automatic identification technology (RFID) and new storage solutions in warehouses in industrial enterprises. Specifically, this study explores how the integration of the Internet of Things (IoT) into warehouse operations can eliminate waste in time and materials. Furthermore, by implementing the PDCA cycle, this provides practical insight into how IoT solutions can create more efficient, responsive, and sustainable logistics processes.

For this case study-based article, the research question and hypothesis can be formulated as follows:

Research Question: How can the implementation of automatic identification technology (RFID) and new storage solutions, integrated with the Internet of Things (IoT), streamline production logistics and reduce waste of time and materials in automotive industry using the continuous improvement by PDCA cycle?

Hypothesis: The implementation of RFID technology and IoT-based storage solutions in industrial warehouses, guided by the PDCA cycle, will significantly reduce time and material waste in the automotive industry, leading to more efficient and sustainable production logistics processes. This hypothesis reflects the assumption that RFID and IoT technologies, when systematically applied, can improve logistics operations by improving real-time tracking, inventory management, and overall efficiency.

2 Literature review

The concept of lean thinking helps eliminate logistics activities that do not add direct added value to the company. Many authors discuss the implementation of digitalisation and the Internet of Things as potential for eliminating waste, improving efficiency [6-11] and sustainability [12-15]. In the theory of logistics and production, waste is, as understood, often anything that adds cost to a product or service without increasing its value. Everything that the customer does not want to recognise as value and pay for is considered as waste. Therefore, every company strives to produce without waste. This issue might be very difficult to achieve, but by constantly reducing waste and combining several methods of industrial engineering, it can be possible to eliminate waste to a minimum level.

In terms of waste definition, it can be specified as waste of time (waiting for a trolley, for work assignment), non-conformity (scrap, wrong assignment of work), unnecessary stocks (excess stocks of finished products, work in progress), overproduction (production of more pieces than the next process consumes), not necessary transport (redundant transport, lengthy transport) and not necessary movements (redundant movements).

Katayama, H. [9]characterised conceptual legends of lean management as follows: perfect elimination of Muri (Strain), Mura (Variegate), and Muda (Waste) on the Plan, Do, Check, and Action Cycles (PDCA).

MURI: That is, a massive resource overload. This is the opposite case to MURA. In the short term, this type of transport can have a positive effect, but as time increases, the wear and tear of the transport machines increases, their performance decreases, and the entire logistics system becomes overloaded.

MURA: Translated in English means unevenness. It deals with under-utilisation of resources; that is, we cannot effectively fill the capacity of our transport machines, which transport material half-empty.

MUDA: The meaning is translated in English as waste, uselessness or purposelessness, which is contrary to the creation of added value. Value-added work is a process that increases the value of a product or service so that the customer is willing to pay for it.

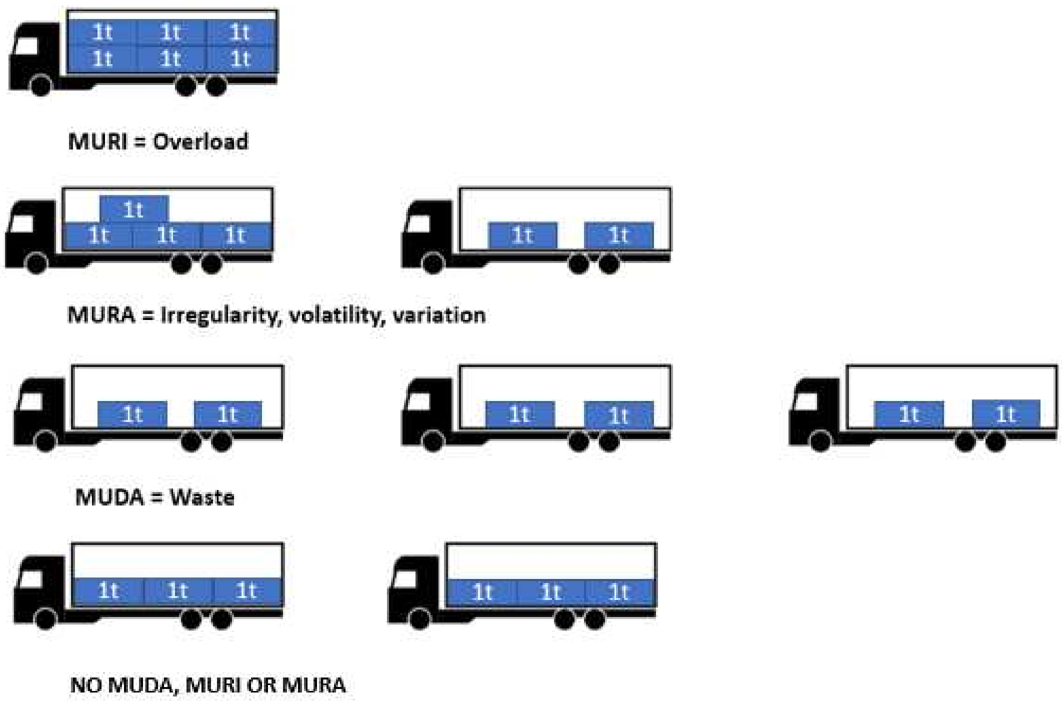

Figure 1 Types of waste in production logistics: mura, muri, muda

Two types of Muda can be defined, namely type 1 and type 2 (Figure 1). Muda type 1 includes activities in processes that do not add direct value to the final product, but are necessary to ensure the quality and safety of the product for the customer. An example can be inspection and safety tests, which do not provide value in themselves but are necessary for the safety of the product. Muda type 2 includes activities in processes that do not add value to the product and are not needed by the customer. These activities should be completely eliminated, ideally, because they do not contribute to improving the quality or value of the product to the customer. The ideal point is to reach the state described as zero muda.

The key principles of the strategic approach Industry 4.0 include the Industrial Internet of Things, cyberphysical systems, vertical and horizontal software integration, augmented reality, predictive manufacturing, logistic and maintenance, autonomous robots, additive technologies, mass individualisation, innovative methods for collecting and processing big data, and many other real-time data analysis techniques utilising the potential of cloud computing [12]. The Internet of Things creates an industrial system that combines intelligent machines, advanced predictive analytics, and machine-human collaboration to promote efficiency and reliability [16]. The IoT is a system composed of heterogeneous devices and organised as networks. Each device (a thing) is equipped with unique identifiers and the capability to share information or transmit data using a wireless or cable network without the need for human interaction.

RFID (Radio Frequency Identification Technology)is a major prerequisite for the Internet of Things (IoT), which, as part of Industry 4.0 connects physical objects to the Internet [12]. Radio frequency identification is a wireless communication technology that uses radio signals to identify specific targets and read and write related data without the need for mechanical or optical contact between the system and a specific target to determine. RFID is an efficient means of identification and one of the main sources of data in the supply chain [7].

The implementation of radio frequency identification is a very interesting and widespread solution in industry to implement IoT systems or distributed sensor networks [9]. RFID represents an innovative tool in warehousing that enables automation of the identification and tracking of materials and products. When combined with lean principles, RFID can significantly improve inventory accuracy, reduce errors in storage and dispatch, and thus improve the efficiency and transparency of logistics operations [3].

By combining lean principles with RFID's tracking capabilities, enterprises can achieve a higher level of efficiency, minimise waste, and ensure timely delivery of products. For example, RFID can provide real-time data that supports JIT inventory systems, enabling companies to reduce excess stock and associated costs. Furthermore, the continuous improvement culture can drive the effective implementation and use of RFID technology, ensuring that the technology is used to its full potential. The wide use of RFID in logistics flow and its potential are presented in [17,18].

Nowadays, RFIDs are relatively cheap, provided by unique identifiers and can be equipped with a variety of sensing capabilities [9]. The advantage of RFID is its extremely low price and its simple methods of production. However, there are definitely limitations that need to be noted, such as the amount of information required during implementation. On the other hand, Katayama [9] considers this limitation to be much less serious or irrelevant.

Data volumes in each supply chain can be generated from various sources of data, business processes, and IT systems, including enterprise resource planning (ERP) systems; order and transport logistics; customer purchasing patterns; and technology-driven data sources such as global positioning systems (GPS), radio frequency-based identification (RFID) tracking, mobile devices, and others [7].

The application of bar code and RFID technologies in logistics, as the most common forms of auto-ID technology, enables fast and enables product identification and supports the logistics flow, including production logistics, transport, handling, warehouse and sales operations, thereby reducing lead time, operational costs, and transaction costs [10,19,20].

3 Methodology

The proposed solution is based on an analysis of the literature, including case studies and previous practices and research. Following the main aim is increasing elimination of waste in the industrial enterprise and continuous improvement the PDCA cycle was applied.

The PDCA methodology can be applied to all processes, including logistics. The Demings cycle, also called the PDCA cycle consists of four phases as follows:

- **Plan** requires the setting of the objectives and processes necessary to achieve the desired results in accordance with the customer requirements.
- **Do** means implement the action plan to achieve the objectives.
- **Check** means monitor and measure processes and products, compare it with stated objectives and indicators.
- **Act** is taking action to improve process performance.

In a study conducted in industrial enterprise using the idea of continuous improvement by the PDCA cycle, the three most significant deficiencies and waste were identified in the logistics flow in an a kitting warehouse in industrial company.

- **Plan:** First, during the planning phase, processes were identified. The task was to increase the efficiency of tracking the kittling trucks in the warehouse and to improve the clarity of the kittling trucks.

- **Do**: The introduction of the selected innovation took place: RFID technology in the warehouse. This solution included the selection of suitable devices (RFID tags and readers), the design of an implementation plan (taking into account time and financial constraints), and the defining the implementation schedule of the solution itself, including the budget. The realisation includes activities necessary for the purchase of RFID tags and readers, the installation of RFID antennas, and reading devices.
- **Check**: During this phase, the performance of the RFID system was monitored and data about the use of the RFID system in logistics were collected and analysed. The focus was mainly on the identification of specific areas for improvement in this project.
- **Act:** During this phase, corrective measures were implemented based on previous actions, and opportunities for standardising these new measures were identified to facilitate continuous improvement.

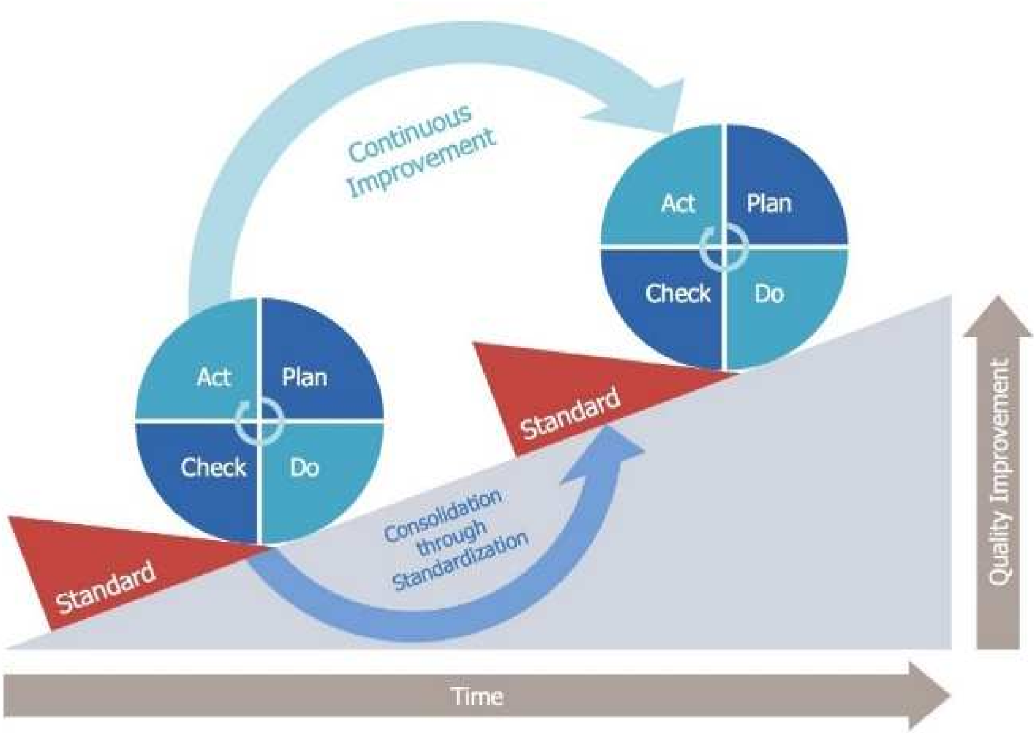

Figure 2 PDCA cycle (https://www.cems-en.com/article/820-pdca-cycle)

The implementation of the PDCA cycle (Figure 2) for identification of shortcomings, planning and realisation of corrective measures to eliminate waste (time, material) in logistics process and verification of implemented solutions result in time savings, workplace optimisation, and scrap minimisation and improving of logistics processes. The solutions themselves were implemented, and their effectiveness was verified by measurement.

4 Results and discussion

This part of the paper focusses on the presentation of an innovative logistics solution in an a case study in industrial enterprise and validation of the research. The object of the analysis was an industrial company that produces interior components for the automotive industry. The organisation was chosen for improvement due to its use of innovative approaches to production and its strong commitment of management to quality and innovation.

4.1 Identification of deficiencies in terms of material flows in the industrial enterprise

Based on the concept of lean philosophy and the analysis of logistics processes, specific steps were implemented to optimise movement flows and the arrangement of warehouse spaces, which could contribute to further increasing the efficiency and overall success of the company within the competitive automotive industry.

The main focus was to plan the improvement of logistics processes in the pilot project in the Kitting area with several innovative technologies. During the workplace, some innovative technologies and also some opportunities for improvement were identified, as well as potential shortcomings. The use of innovative solutions, e.g. the pick-to-light system, was considered to be an effective tool, increasing the accuracy and speed of the work used during the selection of parts from the warehouse. The use of smart gloves to scan the cable enables easier handling of small parts and a reduction in unnecessary movements. Subsequently, several areas of production logistics were identified where improvements could be made.

First, one of the main problems was the inefficient movement of operators when retrieving parts from the racks as the actual layout of the racks was inappropriate, often causing time delays.

Second, there was a need to replace cardboard boxes. Standardizing the packaging could enhance process efficiency in terms of time

The third challenge was inadequate waste management during the work process. Empty packaging thrown by operators on the ground slowed the process and posed a safety risk.

Fourth, the last problem to be solved was the impaired identification of specific kitting tracks due to their uniform construction, design and colour design. It was a challenge for the operators to recognise the kitting trolley.

4.2 Measures for streamlining and innovative solutions in logistics

The first technology introduced to streamline the logistics workflow and avoid waste and waste of time and material in the workplace is radio frequency identification. In this case, this method of automatic data collection using radio waves would be used directly in the kitting warehouse to simplify the identification, tracking, and movement of kitting carts, which serve to assemble the door panel. The main reason for this IoT technology is to prevent waiting times and to prevent blocking of primary production batches.

The problem that might be prevented is where the assembled door does not pass the final quality control due to a defect. Subsequently, such doors cannot be stored in the final container that is intended for final delivery to the customer. Setting up is consider as a waste because the faulty door has to be reassembled with new parts. The line transmits the information to the warehouse, where a new document with identical components is reprinted. The problem occurs at the moment when these priority components are mixed into another batch of kitting carts. As a priority, it is necessary to produce this door in required quality, amount and on time so that the final container can be closed, scanned and handed over to the customer. If this priority kitting cart is mixed with another batch among several different kitting carts, it is problematic for warehouse operators to find this priority cart and immediately send it to the assembly line. The proposed solution is the application of RFID led tags. Using RFID for monitoring, the desired kitting truck can be found and selected from the rest in seconds. The RFID led tag might be placed on the visible top of the kitting cart using a magnetic mount. At the beginning of the process, the warehouse worker scans the QR code in the documentation. Using IoT technology, this information is transferred to the reader and, by subsequent attachment of the RFID led tag, this information can be transferred to a specific tag.

The advantage of implementing the RFID led tag would occur during a specific search for the truck. The LED light built into this device, together with sound signalling, reduces the search for kitting carts to a minimum. It is also an advantage that the worker can search for several carts at the same time or the entire production batch. The battery life of an RFID led tag is stated to be 40 months, and the battery can be replaced. The assumed range of the RFID tag is set at a distance of 30 metres.

The second measure to improve logistics flow was the introduction of a drop rack to avoid used empty packaging. By implementing this measure, the prevention of waste in the form of accumulated empty boxes that warehouse operators place on the ground. When empty packaging and boxes are placed freely on the ground in this way, there is a risk that operators may stumble while working and an accident will occur. The second aspect is as an obstacle in the movement of operators when filling the kitting carts and it affects their handling space in the warehouse. Drop rack are a special type of racks that is used to collect and then remove unnecessary boxes from the workplace without the energy supplied. They are designed with a slope between the beginning and end of the rack, through which the empty boxes can move forward independently. The most useful type of drop for this solution shelf is one with rails. For the solution, a total of six flow racks with dimensions of 280 x 60 x 106 cm (length, width and height) were needed each. For efficient movement at workplace, three pieces of flow rack were needed, each on the right and left sides. After the implementation of these storages, it became easier for logistics operators to handle empty packaging.

In the introduction of the unification of containers, this measure was directly related to the one described previously. The main identified problem was the complicated handling of packaging operators. We found that non-standardised packaging increases significantly handling time. Such cardboard packaging tears and breaks during use, with the risk of damage to the stored material. Operators usually cut a hole in the front of the cardboard box to improve access.

The proposed measure to streamline logistics flow is the purchase of plastic containers with a cutout on the front part. Such packaging would be regularly filled by logistics operators from the original cardboard boxes. The main advantages of the proposed solutions are their strength, accessibility, and low weight. At the same time, these new standardised containers can be stored on racks so that the components stored in them would have a logical connection and continuity in cooperation with the implemented pick-to-light system. This would prevent unnecessary walking between the left and right shelves.

The dimensions of the plastic container are 200 x 310 x 500 millimetres (height, width, and depth). The advantage is the possible stack ability and the possibility to reuse for a long time.

4.3 Verification of innovative solutions

After the introduction of automatic identification with RFID led tags, the efficiency of finding the right kitting truck has increased. For the verification phase, first the measurement of five operators were conducted followed with five measurements with five purchased RFID tags were in the workplace. The data clearly demonstrate significant reductions in time demand across all operators, reflecting the effectiveness of the applied measures. The Table 1 provides a comparative analysis of the time demand for five operators before and after the implementation of improvement measures aimed at optimizing the efficiency of logistics operations.

Table 1 Comparative analysis of the time demand after implementation of measures

	Time demand before [s]	Time demand after measures [s]	Saved time [s]
Operator 1	154	10	144
Operator 2	145	12	133
Operator 3	136	11	125
Operator 4	160	9	151
Operator 5	141	12	129
Total	736	54	682

After statistical analysis of data (Table 2), we can state that the mean time demand of five operators before was 147.2 seconds, with a standard error of 4.35 seconds, indicating moderate variability in the sample. The median time, 145 seconds, suggests that half of the operators completed their tasks in less than this time, while the other half took more time. Notably, there was no mode, indicating no repeated values among the operators' time demands. The standard deviation of 9.73 seconds shows a moderate degree of variability in the times before the measures, with a sample variance of 94.7 confirming this spread in the data. The range of 24 seconds (with a minimum of 136 seconds and a maximum of 160 seconds) further reflects the spread in time demand among the operators. The skewness of 0.34 suggests that the distribution was slightly positively skewed, with a longer tail on the right, indicating that a few operators took considerably longer to complete their tasks. The negative kurtosis value of -1.56 reveals that the time demand distribution is flatter than a normal distribution. The 95% confidence level of 12.08 seconds suggests that the true mean of the population lies within this range, highlighting the precision of the sample mean.

On the other hand, the time demand after the implementation of the measures was reduced, with a mean time of only 10.8 seconds, reflecting the significant improvement in operational efficiency. The standard error also decreased to 0.58 seconds, indicating much greater precision in the post-intervention time measurements. The median time demand was 11 seconds, closely aligned with the mean, demonstrating consistency in the time improvements across the operators. The mode of 12 seconds suggests that this was the most frequent time recorded after the intervention. The standard deviation after the measures was reduced to 1.30 seconds, indicating lower degree of variability compared to the pre-previous measurement. This reduction is further confirmed by the sample variance, which dropped from 94.7 before the measures to just 1.7 after. This suggests that the time demand was much more uniform after the improvements. The range of 3 seconds (with a minimum of 9 seconds and a maximum of 12 seconds) shows a minimal dispersion in time demand following the intervention, reinforcing the notion of enhanced consistency among operators. The skewness value shifted to -0.54, indicating a slight negative skew, where the distribution is now slightly left-skewed, with most time demands being on the lower end. Additionally, the kurtosis value of -1.49 is similar to the pre-intervention kurtosis, indicating that the time demand distribution remained somewhat flat even after the measures were applied. The 95% confidence level after the measures was 1.62 seconds, significantly narrower than the confidence level before the measures.

In summary, the descriptive statistics presented in the Table 2 demonstrate improvement in the efficiency of the operators following the implementation of the measures. The mean time demand decreased from 147.2 seconds to 10.8 seconds, and the variability in time demands significantly reduced as evidenced by the lower standard deviation and variance. The skewness and kurtosis values, along with the narrower confidence intervals, suggest that the improvements were not only effective but also consistent across the operators, resulting in more uniform performance outcomes. These findings provide strong empirical support for the effectiveness of the intervention in optimizing the logistics processes within the industrial setting

In the presented case for logistics, for the complex solution, 40 pieces of RFID tags have to be purchased, one for each kitting trolley used at the workplace. Subsequently, two RFID readers are required to use RFID technology. After the introduction of automatic identification using RFID led tags, the efficiency of searching the kitting trucks has been significantly increased.

At the same time, the realised measures contributed to optimising the removal of empty boxes and packaging from the warehouse. The operator's work is easier, and potential safety risk is avoided with removal of empty boxes on the ground, and simple solution for storage in the flow racks works eliminated waste of time in logistics. The costs for one drop shelf are 335 euros. In the Kitting warehouse, six flow shelves were purchased for total costs of 2010 euros.

Table 2 Descriptive statistical analysis of the time demand after improvement

	Time before measures		Time after measures
Mean	147.2	Mean	10.8
Standard Error	4.352011029	Standard Error	0.583095189
Median	145	Median	11
Mode	no	Mode	12
Standard Deviation	9.731392501	Standard Deviation	1.303840481
Sample Variance	94,7	Sample Variance	1.7
Kurtosis	-1.55800176	Kurtosis	-1.487889273
Skewness	0.342570225	Skewness	-0.541387051
Range	24	Range	3
Minimum	136	Minimum	9
Maximum	160	Maximum	12
Sum	736	Sum	54
Count	5	Count	5
Confidence Level (95.0%)	12.08311972	Confidence Level (95.0%)	1.618931785

Replacement of the original cardboard boxes will bring many benefits to warehouse operators. Operators will not waste move in the form of cutting access to the box. The handling in the logistics flow will also be improved due to the fact that their original cardboard will no longer tear and. get stuck on the shelves. The stack ability of containers is also an advantage for storage. For the workplace, 54 containers need to be purchased for the amount of 6.7 euros, with estimated costs of 368.1 euros.

In summary, the results presented in this case study are consistent with objective and validate the stated hypothesis, showing that RFID technology and new storage solutions significantly improved logistics efficiency and reduced waste.

5 Conclusions

The study focused on an innovative logistics solution considering the improvement of current state of digital transformation in Industry 4.0 and its technologies in the logistics processes in automotive industry, focussing on a case study of an industrial enterprise. The aim of the study was to promote a more efficient solution in logistics by implementing automatic identification technology (RFID) and innovative warehouse management solutions.

By integrating the Internet of Things (IoT) into the PDCA cycle, the research highlighted implementation of s innovative methods for reducing time. The mean time demand decreased dramatically from 147.2 seconds to 10.8 seconds, and the variability in time demands significantly reduced as evidenced by the lower standard deviation and variance. Key improvements observed and measured included increased efficiency in tracking kitting trucks, efficient organisation and sequencing of kitting trucks, and standardization of box unification. These improvement resulted in significant time savings, improved workplace conditions, reduced scrap, enhanced quality control, and overall advancements in logistics performance. which led to significant time savings, workplace optimisation, minimization of scrap, increased quality and overall improvement of logistics processes.

The findings indicate the potential of future innovative lean solutions to increase the efficiency of logistics in industrial enterprises. Several authors emphasize the importance and relevance of sustainable solutions, new technologies, and the digitisation of industrial practice [21-26]. In future research, we will contribute to [27] and continue to explore IoT development, using advanced data analytics, application of emerging technologies applications in logistics, such as blockchain for supply chain transparency and security, while focussing on sustainability . Specifically, future research directions will be essential to maintain and multiply the added value and efficiency achieved through current innovative solutions in context of sustainable development goals, ensuring the continuous optimization of industrial logistics and fostering both economic, social and environmental benefits in the long term.

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Evaluating the performance of tourism supply chain management of tourism companies from the perspective of customer experience

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Keywords: tourism, supply chain, performance, tourism companies.
Abstract: This paper examines the performance of tourism supply chain management (TSCM) in Southeast Vietnam, with a focus on customer experience. Based on Porter's value chain theory, the research divides the tourism process into four key stages: Successful Booking, Pre-traveling, On-traveling, and Post-traveling. Each stage is analyzed for its effect on customer satisfaction and service quality. The findings show that the On-traveling stage has the most significant influence on the overall travel experience, closely followed by the Successful Booking stage. These results highlight the importance of delivering high-quality services during the trip and ensuring a seamless booking process. To evaluate TSCM performance, a survey of 350 frequent travellers was conducted, using the Fuzzy Analytic Hierarchy Process (F-AHP) to assess various criteria, such as accommodation services, information accuracy, and destination attractiveness. The analysis revealed that the On-traveling stage (TRA = 0.4475) is the most crucial, followed by the Successful Booking stage (BO = 0.3408), Pre-traveling (PRE = 0.1365), and Post-traveling (POST = 0.0752). Key factors influencing customer satisfaction include accommodation services (TRA2 = 0.1667) and information accuracy (BO1 = 0.1642). The study emphasizes the need for accurate information throughout the customer journey and improved post-trip interactions to build loyalty. By providing a two-tiered evaluation framework, the research offers theoretical and practical insights for tourism managers to enhance service delivery and customer satisfaction, serving as a foundation for future research on TSCM performance.

1 Introduction

Today, the service industry has rapidly become one of the key sectors of the global economy. The most intense competitive activities in the world are taking place mainly within this sector. Over the past few years, the service industry has experienced significant growth, especially in developing countries. The service sector not only plays an important role but is also a major driver of economic growth in many countries [1]. Within the current service sector, tourism is considered a vast field that encompasses various economic industries such as transportation services, restaurants, hotels, handicrafts, and tourist destinations. This makes ensuring service quality in the tourism industry more complex than in other service sectors. Companies in the aforementioned industries are regarded as the supply chains of the tourism industry and also the supply chains of tourism companies. Only when the links in the supply chain operate efficiently and quality is ensured can competitiveness and profitability be enhanced. The competition among companies in the service sector is fierce, and their success or failure depends on their supply chains [2]. Although the domestic tourism industry was heavily impacted by the COVID-19 pandemic in 2020 and 2021, it has positively recovered post-pandemic, especially in domestic tourism. Additionally, the achievements recognized by global awards (such as the World Travel Awards) affirm the continued significance of tourism within Vietnam's economy and globally. Tourism supply chain management is a relatively new field in Vietnam, yet it plays a crucial role in the industry's development. The components of the tourism service supply chain include First-tier suppliers, second-tier suppliers, tourism companies (tour operators), travel agents, and customers [3]. The primary goal of tourism supply chain management is to satisfy tourists through both the products and services they receive. Tourist satisfaction can be viewed from two perspectives, overall satisfaction with tourism products and satisfaction with individual service aspects provided. Measuring the service supply chain involves evaluating the stages of booking-pre-traveling-on-traveling-post-service delivery [4] and measuring according to service management processes [1]. To measure supply chain management performance, managers need to understand their type of supply chain and know how to apply performance measurement methods. Several methods and techniques for measuring supply chain management performance have been systematized through research, including Process-based approaches, the

Balanced Scorecard (BSC) method [5], and the Supply Chain Operations Reference (SCOR) model; hierarchy-based approaches, simulation techniques including the Analytic Hierarchy Process (AHP) [6], and Data Envelopment Analysis (DEA). Additionally, some studies are based on the TOPSIS model (Technique for Order Preference by Similarity to Ideal Situation) [7], the TOPSIS model combined with Fuzzy Logic [8-10]. Each approach offers a distinct perspective depending on the researchers' viewpoints.

2 Literature review

The main focus of the supply chain in the tourism industry is customer satisfaction. Many companies have failed to fully exploit the potential of their supply chains because they have not yet found the solutions and necessary metrics to integrate into a complete supply chain. Meanwhile, current research on supply chain performance metrics tends to focus internally and does not extend across the various supply chain members. Most measurement frameworks have been developed based on the characteristics of the service industry. Services have distinct features such as intangibility, inseparability, heterogeneity, and perishability [11]. Based on these characteristics, Baltacioglu et al. [12] and Ellram et al. [13] began developing research models for the service industry supply chain. In their research, the core processes that need to be controlled in the service industry include six processes, Information and technology management, demand management, capacity and resource management, supplier relationship management, service operation management, and financial management. Measuring the performance of a company's supply chain management aims to engage all members of the supply chain and achieve their objectives, such as improving service quality, enhancing financial efficiency, and increasing customer satisfaction across the entire supply chain. Although foundational theories exist, research on measuring service supply chain management performance, especially in tourism, remains limited compared to studies in manufacturing industries. The evaluation criteria from previous studies primarily focus on assessing the performance of industrial supply chains. Some prominent studies on service industry supply chain management frameworks include works by Rio et al. [4], Zhang et al. [14], Dawei [15], Ţigu & Călăreţu [16], Palang & Tippayawong [17], Joshi, Sharma, & Keller [18], Nagariya et al. [19], Yang [20], and Heebkhoksung [21]. Porter [22] was the first to introduce the concept of the "value chain", stating that each company comprises a series of activities performed to design, produce, market, distribute, and support its products. Building on this concept, the tourism value chain has been developed by various authors such as Rio et al. [4], Romero & Tejada [23], Song et al. [24], and Yilmaz & Bititci [25], who have constructed frameworks for evaluating tourism SCM performance. In terms of analytical techniques, these studies have developed performance evaluation scales for service and tourism supply chain management using techniques such as AHP, Fuzzy-AHP, TOPSIS, AHP-TOPSIS, F-AHP, IPA, SCOR, and Delphi. However, these studies are limited in several aspects, such as stopping at supplementing the theoretical framework without empirical validation [2,14], and not adequately covering and representing the survey subjects [4,17,18]. Furthermore, in Vietnam, there is currently no research on developing a performance evaluation scale for tourism supply chain management. Therefore, it is necessary to design and develop a comprehensive tourism supply chain management performance evaluation scale based on surveys of managers and tourists with appropriate criteria. From these observations, it is evident that an extensive study on evaluating tourism supply chain management is needed, with full representation of survey subjects and suitable techniques for the research. Currently, there are very few studies measuring the performance of the tourism industry, particularly the tourism supply chain. To build a performance measurement scale for the tourism supply chain, it is essential to develop a tourism supply chain performance scale from the customer's perspective. They are the ones who directly interact with services provided by supply chain members such as transportation, accommodation, restaurants, and other activities. Measuring performance from the customer's perspective will provide clearer insights into service quality, customer satisfaction, meeting needs, and the reliability of partners within the tourism supply chain. Southeast Vietnam has 6 out of 8 provinces/cities belonging to the key economic region of southern Vietnam, including Ho Chi Minh City and the provinces of Ba Ria - Vung Tau, Dong Nai, Binh Duong, Binh Phuoc, and Tay Ninh. This is a dynamic economic region leading the process of industrialization and modernization in the country. Not only leading in these two areas, but the service sector here is also equally vibrant especially tourism. For these reasons, the author has chosen Southeast Vietnam to develop criteria for evaluating the performance of tourism supply chain management of tourism companies in this region through customer surveys.

Given the urgency and practical importance of this issue, the author decided to select the topic "Evaluating the Performance of Tourism Supply Chain Management of Tourism Companies in Southeast Vietnam from the Perspective of Customer Experience". Based on Porter's [22] "value chain" theory and the conceptual framework for measuring tourism SCM performance by Rio et al. [4,9] and Yilmaz & Bititci [25], the author develops the research hypothesis, which includes four main criteria (Level 1), Successful Booking Stage, Pre-traveling Stage, On-traveling Stage, and Post-traveling Stage. These are further expanded into sub-criteria (Level 2) under each of the four stages in Level 1 as follows: Successful Booking Stage, Accuracy of Information; Flexible Booking Cycle Time; Complaint-free Booking Service; Service flexibility; Pre-traveling Stage, Information security; Pre-departure agreements; Accuracy of Information at Destination; On-traveling Stage, Transportation services; Accommodation services; Services of the travel company/travel agent; Destination attractiveness; Resource utilization efficiency; Support from the local community; Post-traveling Stage, Customer satisfaction survey; Customer feedback; Financial performance. To achieve the research objectives, the research team applied the Fuzzy Analytic Hierarchy Process (F-AHP) to evaluate the weights of the factors affecting the tourism supply chain management performance of tourism companies from the customer's perspective. By interviewing 12 experts using the Delphi method, the author eliminated 3 criteria, leaving 13 criteria to proceed with the subsequent research steps (Figure 1).

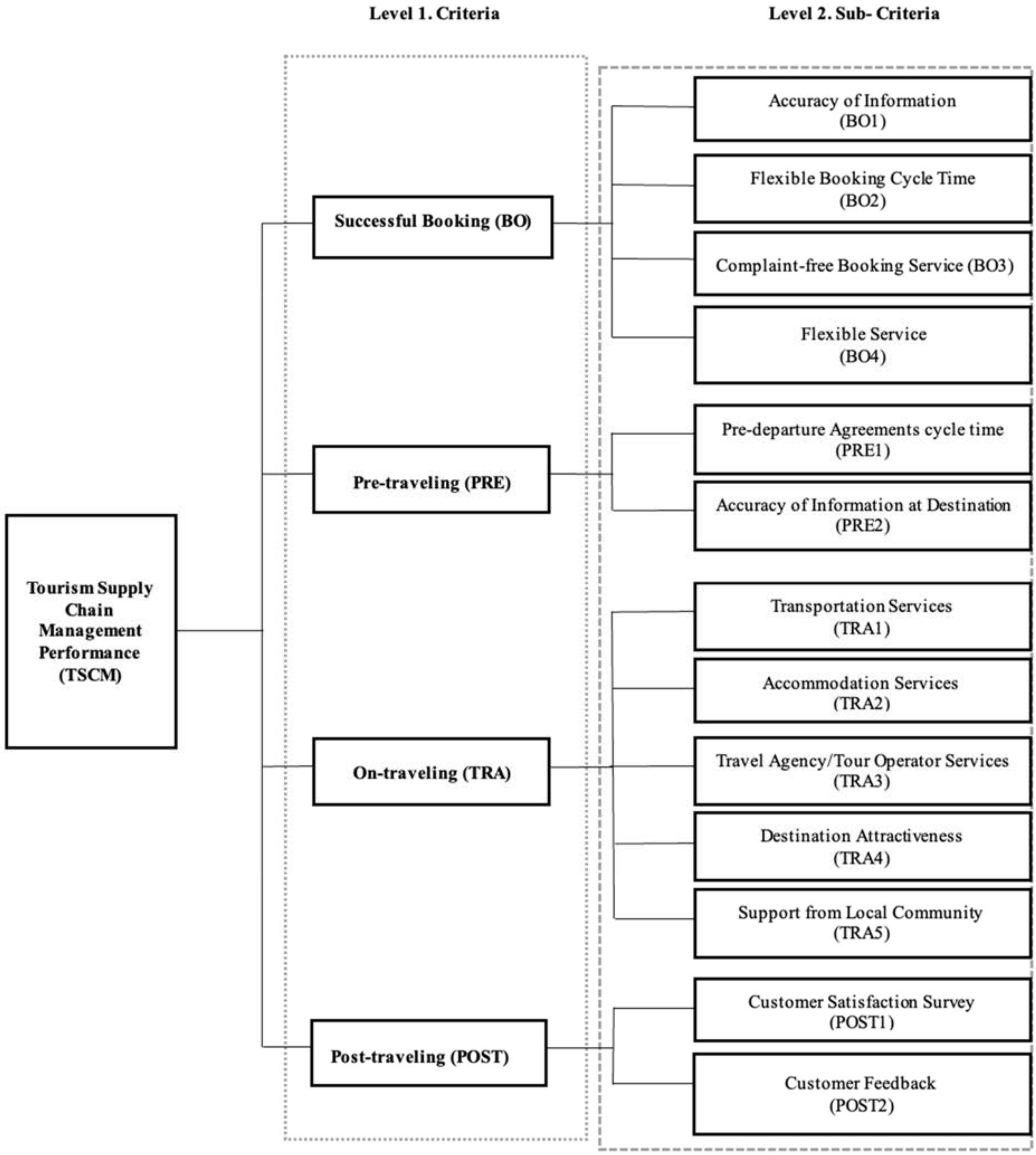

Figure 1 Hierarchical structure model for evaluating supply chain management performance

3 Methodology

3.1 Sampling method

Before conducting the tourist survey, the author performed a preliminary study with 16 experts to confirm that the consistency ratio met the required standards. The research team then employed the Comrey & Lee method [26] to gather 400 data points. After a thorough screening and verification process, 350 valid samples were selected for analysis. As detailed in Table 1, the gender distribution of these samples was as follows: 126 males (36.00%), 216 females (61.71%), and 8 respondents who chose not to disclose their gender (2.29%). This sample size of 350 is categorized as 'good' according to the evaluation scale, which ensures high reliability and accuracy in data analysis, particularly when utilizing complex analytical methods such as the Fuzzy Analytic Hierarchy Process (F-AHP).

Table 1 Demographic statistics

Category	Frequency	Percentage (%)
Gender	**350**	**100**
Male	126	36.00
Female	216	61.71
N/A	8	2.29
Field of Occupation	**350**	**100**
Logistics and Supply Chain Management	93	26.57
Travel and Tourism	87	24.86
Business and Management	44	12.57
Education and Training	41	11.71
Information Technology	24	6.86
Communication and Marketing	33	9.43
Healthcare and Medical Services	16	4.57
Others	12	3.43
Age	**350**	**100**
20-29	49	14
30-39	81	23.14
39-40	97	27.71
40-49	67	19.14
Trên 50	45	12.86
N/A	11	3.14
Nationality	**350**	**100**
Domestic	287	82
International	63	18

3.2 Data processing method

In this study, the author employs the Fuzzy Analytic Hierarchy Process (FAHP) to measure the weights of factors influencing the performance of tourism supply chain management from the customer's perspective. The AHP method is based on the Analytic Hierarchy Process (AHP) framework, which is one of the most widely used methods in multi-criteria decision-making across fields such as management, business, and engineering, where decisions must be made based on various factors, evaluating the priority levels among criteria, and choosing between different options [6] (Saaty, 1980). However, a limitation of the AHP method is that the judgments of respondents are often uncertain, vague, and may not fully represent the actual assessments [27, 28]. To overcome this limitation, the Fuzzy Analytic Hierarchy Process was developed by combining Saaty's AHP [6] with Zadeh's fuzzy theory [29]. Fuzzy set theory, introduced by Zadeh, provides the basic concepts and definitions related to fuzzy sets, extending traditional mathematical concepts to address ambiguous situations in reality. A fuzzy set is characterized by a membership function, which determines the degree of membership of an element in the fuzzy set with a value ranging from 0 to 1.

$$\forall x \in X, \mu_A(x) = \begin{cases} 1 \; if \; x \in A \\ 0 \; if \; x \notin A \end{cases}$$

A fuzzy set can be defined as follows, Let X be a set of elements. A fuzzy set is a set represented as a membership function µA(x), which indicates the degree of membership in set A. If µA(x) = 0 it means the element does not belong to set A at all, whereas if µA(x)=1 it means the element fully belongs to set A.

Based on this concept, the FAHP method has been applied in previous case studies in the fields of tourism management and tourism supply chain management. The FAHP analysis process includes the following steps:

Step 1: Constructing the hierarchical structure.

Based on the proposed supply chain management performance measurement framework the author develops a hierarchical structure for evaluating the supply chain management performance of tourism companies in Southeast Vietnam (1), (2), (3).

$$A(k) = [a_{ij}^k] \quad (1)$$

$$\boldsymbol{a_{ji}^k} = \frac{\mathbf{1}}{\boldsymbol{a_{ij}^k}} \quad (2)$$

$$A^{(k)} = \begin{bmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{nn} \end{bmatrix} \quad (3)$$

Let *n* be the number of main (or sub) factors included in the research model. Based on the formula nC2 (the combination of n elements taken 2 at a time), the pairs of factors for comparison will be established. Here, a(k)ij represents the evaluation score of the expert regarding the comparison of the factor in row i with the factor in column j, where k. The evaluation score in the lower triangular matrix below the diagonal is the reciprocal of the evaluation score in the upper triangular matrix above the diagonal.

Step 2: Designing the survey questionnaire (Table 2).

Table 2 Survey questionnaire for triangular fuzzy AHP scale [6]

Intensity of importance	Linguistic Definition	Fuzzy Triangular Numbers
1	Equal importance	(1,1,1)
3	Weak importance of one over the other	(2,3,4)
5	Strong importance	(4,5,6)
7	Very strong importance	(6,7,8)
9	Absolute importance	(9,9,9)
2,4,6,8	Intermediate scales	(1,2,3) (3,4,5) (5,6,7) (7,8,9)

Step 3: Triangular fuzzy AHP scale and establishing the fuzzy symmetric matrix.

In this step, a fuzzy symmetric matrix is established based on the theory of triangular fuzzy numbers (Figure 2). Accordingly, a triangular fuzzy number has three values: the smallest value (l_{ij}), the median value (m_{ij}), and the largest value (u_{ij}).

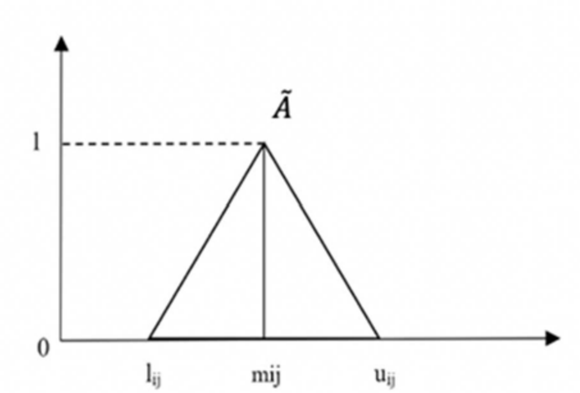

Figure 2 Triangular fuzzy number [29]

$$\tilde{A}^{(k)} = [\tilde{a}_{ij}^{k}] = \begin{bmatrix} \tilde{a}_{11l}\tilde{a}_{11m}\tilde{a}_{11u} & \tilde{a}_{12l}\tilde{a}_{12m}\tilde{a}_{12u} & \tilde{a}_{1nl}\tilde{a}_{1nm}\tilde{a}_{1nu} \\ \tilde{a}_{21l}\tilde{a}_{21m}\tilde{a}_{21u} & \tilde{a}_{22l}\tilde{a}_{22m}\tilde{a}_{22u} & \tilde{a}_{2nl}\tilde{a}_{2nm}\tilde{a}_{2nu} \\ \vdots & \vdots & \vdots \\ \tilde{a}_{n1l}\tilde{a}_{n1m}\tilde{a}_{n1u} & \tilde{a}_{n2l}\tilde{a}_{n2m}\tilde{a}_{n2u} & \tilde{a}_{nnl}\tilde{a}_{nnm}\tilde{a}_{nnu} \end{bmatrix} \quad (4)$$

$$\tilde{a}_{ij}^{k} = \begin{cases} if\ i > j,\ [l_{ij}, m_{ij}, u_{ij}] \\ if\ i = j,\ [1,1,1] \\ if\ i < j,\ \left[\frac{1}{l_{ij}}, \frac{1}{m_{ij}}, \frac{1}{u_{ij}}\right] \end{cases} \quad (5)$$

Step 4: Consistency check.

When comparing pairs of factors in the multi-criteria decision-making matrix, it is easy to encounter inconsistencies in responses. To address this limitation, Saaty (1980) introduced a consistency ratio (CR < 10%) to ensure consistency in the evaluation process.

First, defuzzification must be performed (4), according to formula (5)

$$A_{crisp} = \frac{l+4m+u}{6} \quad (6)$$

for each triangular fuzzy number $\tilde{A}$ (6)

$$W_{ij} = \frac{a_{ji}^{k}}{\sum_{ij=1}^{n} a_{ji}^{k}} \quad (7)$$

where n is the number of factors

Based on the normalized relative weights W_{ij} (7), the official normalized weight W_i (8) of the i, the factor can be calculated, which is the average value across all rows j for i the factor. Subsequently, the matrix X represents the total weighted (9).

$$W_i = \frac{\sum_{ij=1}^{n} W_{ij}}{n} \quad (8)$$

n is the number of elements;

$$X = AW \quad (9)$$

Next, the maximum eigenvalue λ_{max} is the average of the λ values (10), (11):

$$AW = \lambda\ W_i \text{ so } \lambda = \frac{AW}{W_i} \text{ hay } \lambda = \frac{X}{W_i} \quad (10)$$

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \lambda}{n} \quad (11)$$

Consistency Index (12):

$$CI=\frac{\lambda_{max}-n}{n-1} \quad (12)$$

Finally, to achieve consistency in the survey process, the consistency ratio (CR) (13) must be less than 10%. The formula for calculating CR is as follows:

$$CR=\frac{CI}{RI}\ (CR<10\%) \quad (13)$$

RI is the random index (standard) based on the number of evaluation factors according to the following table (Table 3):

Table 3 Random Index corresponding to the number of factors (RI) [6]

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Step 5: Calculating and normalizing the weights of the factors.

From the fuzzy matrix, the author proceeds to normalize using the row geometric mean method (14).

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{1/n} = \left[\left(\prod_{j=1}^{n} l_{ij}\right)^{1/n}, \left(\prod_{j=1}^{n} m_{ij}\right)^{1/n}, \left(\prod_{j=1}^{n} u_{ij}\right)^{1/n}\right], i=1,2,3,...,n. \quad (14)$$

From there, the relative fuzzy weights can be calculated (15).

$$\widetilde{w}_i = \tilde{r}_i \times (\tilde{r}_1+\tilde{r}_2+\tilde{r}_3+...+\tilde{r}_n)^{-1} = (lw_i, mw_i, uw_i) \quad (15)$$

Next, the defuzzified weight M (16) will be calculated using the following formula.

$$M_i=\frac{lw_i+mw_i+uw_i}{3} \quad (16)$$

Finally, the normalized weight N (17) is calculated using the following formula.

$$N_i=\frac{M_i}{\sum_{i=1}^{n} M_i} \quad (17)$$

4 Results and discussion

4.1 Results

4.1.1 Check the consistency of the evaluation process

To check the consistency of the survey data, the first step is to denazify the survey results. The scores in the comparison matrix (Table 4) are taken from the average survey scores of 350 customers. Then, the matrix is defuzzified using formula (5), and formula (6) is used to calculate the relative normalized weights (W_{ij}) of the criteria. Next, formula (7) is used to calculate the official weights (W_i), and matrix X (8). Finally, the eigenvalue λ is calculated using formula (9) (Table 5). This process is repeated for the remaining comparison matrices.

After calculating the eigenvalue, the author uses formula (10) to calculate the maximum eigenvalue (λmax) of the factors. Based on the number of criteria in each comparison matrix (or supply chain stage), the random index (RI) is determined. The consistency index (CI) and consistency ratio (CR) are calculated using formulas (11) and (12). The results are presented in Table 4.

Table 4 Consistency in the Evaluation Process

	Criteria (n)	Random Index (RI)	λ_{max}	Consistency Index (CI)	Consistency ratio (CR)	(CR<0.1)
TSCMP	4	0.9	4.1665	0.0555	0.0617	Accept
BO	4	0.9	4.2387	0.0796	0.0884	Accept
PRE	2	0.0	2.0071	0.0071	-	Accept
TRA	5	1.12	5.2664	0.0666	0.0595	Accept
POST	2	0.0	2.0126	0.0126	-	Accept

4.1.2 Calculate the weights of the criteria

Based on the results of the comparison matrix (TSCM, BO, PRE, TRA, POST), from Table 4, normalization is performed using the row geometric mean method (13), and the fuzzy weights are calculated (14). Then, the defuzzified weight M_i is calculated using formula (15), and the normalized weight is calculated (16).

The table 5 summarizing the performance evaluation results of tourism supply chain management highlights the significance of each stage in the customer journey, including the Successful Booking Stage, Pre-traveling Stage, On-traveling Stage, and Post-traveling Stage. Each criterion is assigned a weight (Ni), reflecting its importance in the evaluation process. Within each stage, sub-criteria are listed alongside their local weights (indicating their contribution within the stage) and global weights (showing their overall impact), along with the ranking of each sub-criterion. This structure helps identify areas for improvement. For instance, "Accuracy of Information at Destination (PRE2)" has the highest global weight (0.0707) and ranks 6th, indicating its critical role in customer satisfaction. Conversely, "Complaint-free Booking Service (BO3)" holds the lowest global weight (0.0339) and ranks 12th, suggesting significant improvements are needed to enhance customer experience during the booking phase. Overall, the evaluation table provides a comprehensive overview of performance and highlights priority areas for improvement in tourism supply chain management.

Table 5 Results of the Tourism Supply Chain Management Performance Evaluation

Criteria	Weight (N_i)	Sub-Criteria	Local Weights	Global Weights	Rank
Successful Booking Stage (BO)	0.3408	Accuracy of Information (BO1)	0.4818	0.1642	2
		Flexible Booking Cycle Time (BO2)	0.1950	0.0665	7
		Complaint-free Booking Service (BO3)	0.0994	0.0339	12
		Service flexibility (BO4)	0.2238	0.0763	4
Pre-traveling Stage (PRE)	0.1365	Pre-departure agreements (PRE1)	0.4818	0.0658	8
		Accuracy of Information at Destination (PRE2)	0.5182	0.0707	6
On-traveling Stage (TRA)	0.4475	Transportation services (TRA1)	0.1397	0.0625	9
		Accommodation services (TRA2)	0.3725	0.1667	1
		Services of the travel company/travel agent (TRA3)	0.1646	0.0737	5
		Destination attractiveness (TRA4)	0.2401	0.1074	3
		Support from the local community (TRA5)	0.0831	0.0372	11
Post-traveling Stage (POST)	0.0752	Customer satisfaction survey (POST1)	0.3827	0.0288	13
		Customer feedback (POST2)	0.6173	0.0464	10

4.2 Discussion

Based on the weighted results of the criteria in the evaluation scale for tourism supply chain management from the customer's perspective, the findings indicate that among the four stages of the tourism supply chain, the "On-traveling Stage" phase is considered the most crucial by customers when experiencing services (TRA=0.4475). This stage significantly influences the overall travel experience that tourists undergo. The "On-traveling Stage" is when tourists directly interact with tourism services and products, including hotels, restaurants, attractions, and entertainment activities. This phase creates a powerful first impression on tourists and profoundly impacts the image of the destination and related services. Following this is the "Successful Booking stage" (BO=0.3408), the "Pre-traveling Stage" (PRE=0.1365), and finally the "Post-traveling Stage" (POST=0.0752), which has the lowest weight, indicating that the connection between the customer and the travel company tends to end after the trip, significantly affecting the improvement of tourism supply chain management outcomes. Travel companies should take measures to enhance post-trip customer interaction to gather feedback and suggestions and to create lasting memories for the customers. This approach increases marketing effectiveness and the likelihood of customers returning for future trips. Advertising stories from customers' memories during the trip serve as one of the most cost-effective marketing tools [30]. Today's younger generation of tourists tends to be interested in cultural lifestyles and practical experiences throughout their travels. Additionally, they often share their travel experiences on social media, indirectly introducing them to a broader audience [31]. Therefore, tourism service providers should minimize this gap to maximize the benefits of marketing.

In the "Successful Booking stage (BO)", the criterion "Accuracy of Information (BO1)" plays the most important role, with a weight of 0.4818, ranking second overall among the evaluated criteria with a proportion of 0.1642. This reflects the importance of providing accurate information to tourists in Vietnam. Nowadays, tourists tend to search for and confirm information multiple times before making a trip. They require clear and detailed information about booking services, prices, cancellation conditions, and additional services like meals, transportation, or entertainment activities. Ensuring the accuracy and transparency of information during this phase not only helps customers make quick decisions but also builds trust and enhances their satisfaction with the company's services. When customers receive full and accurate information, they are more likely to trust the service, leading to a higher likelihood of booking and an overall better experience. On the other hand, "Complaint-free Booking Service (BO4)" is less of a concern, as if a service provider ensures accurate information, the occurrence of complaints naturally becomes less frequent. This flexibility contributes significantly to retaining customers and enhancing their positive experience from the early stages of the travel process. Based on this result, tour providers should focus on accurate information handling to minimize complaints, enhance customer satisfaction, and optimize supply chain operations.

In the “Pre-traveling Stage (PRE)”, the criterion “Accuracy of Information at Destination (PRE2)” has an overall weight of 0.0707, ranking sixth in the overall evaluation. This weight highlights the importance of providing detailed and reliable information about the destination. Modern tourists are highly concerned about factors such as local culture, weather conditions, entertainment activities, and available services at the destination. Providing accurate information not only helps customers better plan their trip but also creates peace of mind and positive expectations for the upcoming experience. Pre-departure agreements (PRE1) also carry a significant weight of 0.0658, nearly equivalent to the other criterion, indicating that preparation and execution of pre-departure procedures remain critical factors in travel decisions. This includes handling necessary paperwork such as visas, pre-booking services, and activities, as well as packing and other personal preparations. Moreover, tourists, especially in the post-COVID-19 era, are very concerned about safety measures, hygiene, and health conditions at the destination, as well as special weather conditions, etc. Providing accurate information not only reassures customers but also helps them better plan their trip. Thorough preparation before departure makes customers feel more confident and minimizes worries about potential issues during the trip. Customers often feel uncomfortable when the trip lacks a specific itinerary and they have to find information on-site [32].

The “On-traveling Stage- (TRA)” holds the highest weight, making it the most critical stage in determining the outcomes of tourism supply chain management. “Accommodation services (TRA2)” hold the highest weight during this phase at 0.3725 and rank the highest overall at 0.1667. This emphasizes the importance of accommodation services to tourists in Vietnam. A good accommodation facility contributes to a pleasant holiday experience, while poor accommodation can significantly diminish the quality of the trip. This is also the stage where customers spend the most time during the entire travel process. Accommodation services can include additional amenities such as dining, room service, and other supplementary services. This importance was also highlighted in previous research by [33]. Following this is “Destination attractiveness (TRA4)”, which ranks second in the “On-traveling Stage- (TRA)” with a weight of 0.2401 and third overall at 0.1074. Factors such as beautiful landscapes, famous attractions, diverse entertainment activities, and unique cultures all play important roles in the tourism supply chain. Destination attractiveness is one of the key factors in a tourist’s travel decision. An attractive destination not only enhances the value and enjoyment of the trip but also significantly contributes to building the reputation and appeal of tourism services. Conversely, “Support from the local community-TRA5” weighs 0.0831, the lowest in the “On-traveling Stage- (TRA)”, possibly due to the type of tourism and customer needs (sightseeing, leisure, or co-creation experiences at the destination, etc.). Therefore, interaction with locals during the trip may be limited, and the likelihood of objective risks requiring local community support is also low.

Finally, the “Post-traveling Stage- (POST)” is the least emphasized stage. The criterion “Customer feedback-(POST2)” is of particular interest to customers, with a weight of 0.6173, providing deeper insights into the tourist experience. Collecting feedback contributes to making customers feel more valued and makes it easier to assess the actual and practical limitations of the tourism supply chain compared to traditional customer satisfaction surveys. This also yields high effectiveness in marketing activities. For instance, establishing a feedback collection and sharing system contributes significantly to marketing efforts through word-of-mouth promotion of the trip experience to others.

5 Conclusions

In conclusion, this study highlights the critical importance of tourism supply chain management (TSCM) in improving customer satisfaction and service quality within Southeast Vietnam’s tourism industry. Grounded in Porter’s value chain theory, the research identified four key stages of the tourism process: Successful Booking, Pre-traveling, On-traveling, and Post-traveling. Notably, the On-traveling stage was found to be the most impactful (TRA = 0.4475), as it directly shapes the tourists' overall experience through services such as accommodations, transportation, and destination attractions. This underscores the necessity of maintaining high service quality in these areas to enhance customer satisfaction and foster repeat business.

The study also underscored the importance of accurate information throughout all stages, with the Successful Booking stage (BO = 0.3408) ranking second in significance. The accuracy of booking information (BO1 = 0.4818) was particularly crucial, as modern travelers demand precise details regarding services, prices, and terms to make informed decisions. Meeting these expectations builds trust, reduces complaints, and improves the overall travel experience.

While the Pre-traveling stage (PRE = 0.1365) ranked lower, the provision of clear and reliable destination information was still essential in managing customer expectations and ensuring smooth trip planning. The Post-traveling stage (POST = 0.0752) had the least influence, indicating a common lack of post-trip engagement by companies. However, improving post-travel interactions—such as soliciting feedback and reinforcing positive travel memories—could significantly boost customer loyalty and drive word-of-mouth marketing, particularly valuable in today’s social media era.

The Fuzzy Analytic Hierarchy Process (F-AHP) was effectively employed to assess TSCM performance, providing a weighted, criteria-based framework for evaluation. Among the secondary criteria, accommodation services (TRA2 = 0.1667), booking accuracy (BO1 = 0.1642), and destination attractiveness (TRA4 = 0.1074) emerged as the most influential factors, further emphasizing the critical role of service quality during the On-traveling stage.

Furthermore, the study calls attention to the importance of post-travel engagement by utilizing customer feedback to gain deeper insights into service quality and supply chain performance. Establishing robust feedback systems not only fosters customer appreciation but also enhances marketing efforts through shared customer experiences.

This research fills a significant gap in the relatively sparse literature on tourism supply chain performance in Vietnam, offering practical guidelines for tourism managers to enhance service delivery, streamline operations, and prioritize customer satisfaction across all stages of the supply chain. By adopting these recommendations, tourism enterprises in Southeast Vietnam can improve their competitiveness, ensure sustainable growth, and build a foundation for future research in TSCM performance.

The evaluation criteria and scale developed in this study are valuable tools for tourism enterprises to optimize supply chain management, enhance service quality, and create exceptional travel experiences. By applying the managerial insights derived from these criteria, businesses can strengthen their competitive edge, achieve sustainable development, and ensure long-term success in the rapidly growing tourism sector. However, this study has some limitations. First, the evaluation survey was conducted from the customer's perspective, which, while useful for decision-making, lacks the comprehensive scale needed from a managerial viewpoint within the supply chain. Second, the Fuzzy AHP method, still relatively new in Vietnam, led to some respondent hesitation despite the author's efforts to clarify the questions during interviews. Lastly, due to geographical constraints, the study's measurement criteria were confined to the Southeast region, limiting the generalizability of the findings. Future research will aim to develop evaluation scales for various stakeholders and expand the survey to cover a broader geographical area.

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Competitiveness supported by the analysis of risk factors of the recall of products process in the production logistics
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Competitiveness supported by the analysis of risk factors of the recall of products process in the production logistics

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Keywords: competitiveness, automotive industry, risk factors, recalls.
Abstract: Nowadays, the automotive giants and the automotive industry are focused on increasing the performance of vehicles and reducing the number of calls to action, which means an increase in costs and loss of customers for automotive companies, which is reflected in reduced competitiveness. The main goal of this paper is to identify the consequences of recall actions in automotive companies, to identify risks, and to determine the dependence between criteria characteristics such as risk size, product quality, frequency of recalls, detection accuracy, and error rate. Within the research part, 5 hypotheses were set, based on which the individual dependencies of the criterion characteristics were determined. The most common cause of calls was electrical engineering and electronics. In terms of error rate, these were design errors. The most called vehicles were Citroen, and the error rate was 3.74%. The greatest risk to the supplier's structure was represented by car bodywork. Call-to-action is an effective tool for automotive companies to take corrective action. The main intention of automotive companies is to reduce the error rate on vehicles and minimize the number of calls to action to increase the competitiveness of automotive giants. The strategic intention of minimizing recall actions is also reflected in maintaining a good reputation with customers - goodwill.

1 Introduction

The recall process in the automotive industry represents a sector of poor quality. This sector is reflected in the poor quality of automotive components in vehicles, the software, electrical, and electronic areas of the vehicle, in the environmental quality, and in complex management and diagnostics of the products. These elements of poor quality must be solved during the design of the vehicles [1]. This article aims to identify the consequences of recall actions in automotive companies, to identify risks, and to determine the dependence between criteria characteristics such as risk size, product quality, frequency of recalls, detection accuracy, and error rate. One part of facility management is the process of call-to-actions of individual cars are carried out based on identified deficiencies that may endanger the health and safety of car users. This process creates a place for improvement of all processes in the automotive industry to fill in the requirements of customers [2]. These recall actions are a risk for car companies that threatens their competitiveness and dominant position in the automotive market and the loss of customer satisfaction [3]. Competitiveness, prosperity, and the ability to create added value in the automotive industry depend largely on the emphasis on the quality of production [4].

The important indicator is green and cleaner production connected with the good choice of suppliers. All those factors are part of the circular economy cycle in the frame of Industry 4.0 and Industry 5.0 [5]. Bates et al. (2007) commented on one of the characteristic features of the current automotive industry is the transfer of responsibility for the management and quality of deliveries from the manufacturer to suppliers [6]. Any errors identified outside the production plant in the form of recall actions can have devastating effects on the production company [7]. Thomsen et al. (2001) presented and commented the call-to-action is an important indicator of the efficiency of the automotive distribution network. The main intention of automotive giants is to reduce poor quality in the form of recall actions, which represent an increase in costs for automotive companies and their suppliers [8]. Fritz (2010) said that the best-known defects of the product in the automotive industry were recorded [9]. Potkany et al. (2022) demonstrated the factors of competitiveness for the automotive industry, and they presented quality management practices that are orientated to defective products [10].

Among the most common causes of recalls was the company BMW. This company banned charging plug-in hybrids from reason to short circuits. The other causes of recalls were recorded in the company Skoda Octavia. They solved a software problem with a malfunctioning emergency e-call. The company Peugeot caught two technical problems that can cause loss of control of the vehicle. The Swedish carmaker Volvo solved the problem in the autonomous brake system. Other automotive companies such as Nissan, Mazda, and Kia had problems with brake assistants. The companies Peugeot, Citroën, Opel, Ford, Range Rover, Jeep, and Bentley had problems with driving some models. Some Ford models had a problem with the risk of fire. The failure of the diagnostic module was solved by a Škoda car on superb models. Mazda had problems with fuel supply in Skyactiv-X systems and others [11]. Those defects in vehicles create risks in products. Those risks increase the cost of quality in the supply chain [12]. The supply chain creates the basis for an effective production process that results in quality products. The application of generally applicable logistics principles may result in increased quality of products. In addition, those principles can improve the efficiency, operability of the machines and equipment, profitability, and liquidity. Those economic indicators are the frame for competitiveness [13].

2 Theoretical background

The automotive industry faces many challenges oriented on performance indicators that stabilize automotive sustainability. The base of automotive competitiveness is lean manufacturing, digitalization, and green economy and environment [14]. Industries such as automobiles, pharmaceuticals, medical devices, electronics, toys, and food have often announced recalls of defective products that introduce safety and health hazards to customers [15]. The quality of products is an important part of Quality 4.0 towards comprehensive product enhancement in the manufacturing sector of the automotive industry [16]. Product safety is a very important indicator of quality products and a main aim for customer satisfaction. The operational management's discovery of product recalls suggests that recalls, particularly those related to lack of safety, are increasing in various industries and sometimes in the automotive industry [17]. Customer satisfaction and product quality create the basis for the company's performance, strategic development and competitiveness [18].

The defective products that are dangerous for customers from various views need to be discovered in the frame of the supply chain. A recall due to a safety hazard occurs because of three main triggers. First, the firm may find the potential for a safety hazard due to a product defect. Second, consumers or downstream supply chain players may report this hazard to the firm. In either case, firms must report the safety hazard within 24 hours. Third, consumers, downstream supply chain players, and competitors may directly contact and inform about the safety hazard posed by a product [19]. In all three of these cases, the firms jointly investigate the product defect and take the necessary action to eliminate the hazard by recalling the product to repair it, replace it, or refund the purchase price [20]. The recall process highlights two main categories of recall strategies for the companies. In the praxis are two types of recall strategy: a preventive and a reactive recall strategy [21]. Govindaraj et al. (2004) explained recall strategies followed: a preventive recall strategy implies that a firm conducts quality checks and inspections. Based on the results of inspections may discover product defects that could potentially pose a safety hazard. Firms can adopt a reactive recall strategy in which they may not proactively scout for product defects that pose a safety hazard, but the investigation process for recalls may be initiated only after a safety hazard has caused injuries or deaths [22,23].

The poor quality of products is caused by a supply chain model that is not prepared for market demand and needs of the automotive assembly companies [25]. The increasing trend of various types of spare parts for automotive companies means more than 4000 outside suppliers, including company-owned spare parts suppliers. This approach needs a strategic global supply chain model [26]. From this view has been important to use instruments of crisis management and solve situations in the spare parts [27]. One of the instruments is predictive maintenance planning that it contents the order and storage of spare parts. This system creates a base for sustainable manufacturing [28]. Sustainable manufacturing in the automotive industry means recording the manufacturing phases during vehicle production. The reason is that the vehicle goes through many different steps during assembly [29]. The modern approach to sustainable manufacturing is implementing TPM (Total productive maintenance) that relates to man, machines, and materials. This synergy effects increase operational performance in the automotive industry, and it means lean production [30,31]. The recall process brings financial losses [32]. It means decreasing returns, increasing costs, and impacting equity. The loss of shareholder value is often substantially greater than the cost of the recall itself, including those associated with destroying or repairing defective products [33]. Product recall events impose costs, affect sales, raise manufacturing costs, dilute brand equity, and hurt the financial value, posing a significant threat to companies. Recall process must be a part of sustainable development with low economic and environmental effects [34]. The effective instrument for the recall process is controlling and its implementation [35].

3 Research objective, methodology and data

Part of the research was focused on recall processes in the automotive industry. The main hypotheses were established to identify the consequences of calls to action in automotive companies. Based on statistical analysis, the dependencies between the criteria characteristics - the size of the risk, the quality of the products, the number of calls to action, the accuracy of detection, and the error rate were determined. Part of the research was the collection of data on recalls and their processing for the preparation of statistical analyses and confirmation of hypotheses.

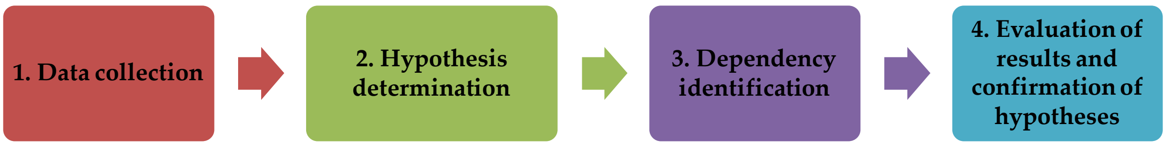

Figure 1 Algorithm of research, source: own research

1. Data collection: part of the research was the acquisition of relevant data for recalls in the automotive industry in the time interval 2005-2015. The research used Google Trends analytical tools, the web portal "vosa.gov.uk", statistical sources of information on the number of vehicles produced in the analyzed period OICA, 2014, as well as summary information obtained by analyzing calls for selected automotive companies VOSA, 2015.

2. Hypothesis determination: [1] claim that the extent of call-to-actions is an important indicator of the efficiency of the automotive distribution network. This argument was the basis for establishing the following research hypotheses for call-to-actions in automotive companies (Table 1).

Table 1 Determination of research hypotheses, source: own research

Number of the hypothesis	Description of the specified hypothesis
Hypothesis number 1 (H1):	• There is a direct relationship between the growth of risk and the growth of stakeholder interest.
Hypothesis number 2 (H2):	• The quality of selected suppliers affects the quality of manufactured products.
Hypothesis number 3 (H3):	• There is an indirect relationship between the number of calls to action and the probability of detecting errors.
Hypothesis number 4 (H4):	• The pressure on accuracy and quality is directly proportional to the timeliness of error detection.
Hypothesis number 5 (H5)	• There is an indirect relationship between the error rate and the size of the risk.

The individual hypotheses were subsequently tested using the analysis of call-to-actions from 2005 to 2015. Various tools were used to analyze the hypotheses (H1) to (H5). The analytical tool Google Trends was used for the tested hypotheses (H1). Research worked with data from the years 2007 - 2015. The frequency of the search term was analyzed concerning the ratio of the total number of searches via Google Trends. For the testing of hypotheses (H2) to (H5), the source of information in the sector of calls was the web portal "vosa.gov.uk", where the sources for analysis were selected based on precisely specified criteria. It worked with recalls that met the basic characteristics of calls listed in Table 2 and Table 3.

Table 2 Basic characteristics of users calls-to-action, source: own research

Characteristic	Identification
Vehicle Age	Less than 8 years
Cost – Bearing	Vehicle manufacturer
Standard Length of Repairs	60 days
Invalidity of The Recalls	Lawsuit
Compensation In Case of an Accident	Not necessary
Impossibility of Repair	Financial compensation

Table 3 Identification of the sources of users calls-to-action, source: own research

Identification of the calling action
http://www.vosa.gov.uk/vosa/apps/recalls/
http://www.recalls.gov/nhtsa.html
http://www.safercar.gov/Vehicle+Owners
http://www.mycarstats.com/reports/recalls.aspx

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3. Dependency identification: In this part of the research, the dependencies of the criterion characteristics were monitored through the analysis of the risks of the recalls according to the assembly groups and the analysis of the causes of car damage. (During testing hypothesis (H2)). Analysis of the timeliness of detection of faulty components was used in testing hypotheses (H3) and (H4). For testing hypothesis (H5), an analysis of error rate was performed (OICA, 2014), as well as summary information obtained by analyzing the recalls of selected automotive companies (VOSA, 2015).

4. Evaluation of results and confirmation of hypotheses: this phase of the research was processed using graphical methods and an error rate based on a relative number (1).

$$F_i = \frac{\sum_{2005}^{2015} ZA_{ij}}{\sum_{n}^{m} V_{ij}} \quad (1)$$

where: (Fi) - error rate, probability of error, (Aij) - called vehicles of individual brands of the analyzed period, (Vij) - total number of produced vehicles during the calling action period (n-m).

Error rate calculation, resp. the probability of error was obtained by dividing the sum of the individual brands of called vehicles (A) of the analyzed period (t) by the sum of the total number of vehicles produced (V) for the range of the period affected by the recalls (n-m) (2).

$$\bar{P}_{ZA} = \left(\sum_{i=1}^{n} \frac{manufacture\ year\ of\ the\ vehicle}{start\ of\ the\ call-to-action}\right) \div n \quad (2)$$

The average probability of error detection (PZA) – the probability of detecting an error represents a ratio of the production years of the vehicle to the time of the start of the vehicle call action. The higher probability and close to the value of p = 1 means the earlier period of error detection on the vehicle. (n) - represents the number of called vehicles.

4 Results and discussion

Within the research of the recall actions, after data collection and processing, it carried out the identification of the dependence based on the established hypotheses, and it evaluated the individual hypotheses based on statistical analyzes.

Hypothesis number 1 (H1):	***There is a direct relationship between the growth of risk and the growth of stakeholder interest.***

In the process of the testing hypothesis (H1), there is a direct relationship between the growth of risk and the growth of interest groups (Figure 1). Google Trends was used. The results were surveyed in the period 2007-2015. The interest of interested groups in the recall actions of selected car brands is assessed based on the level of interest in the analyzed issues in a limited time horizon using the analytical tool Google Trends. The height of the values in the graph represents the frequency of the searching term to the ratio of the total number of searches on Google. The data in the graph are normalized and presented on a scale from 0 to 100. Descending, resp. the rising curve indicates a reduced, resp. increased search term frequency.

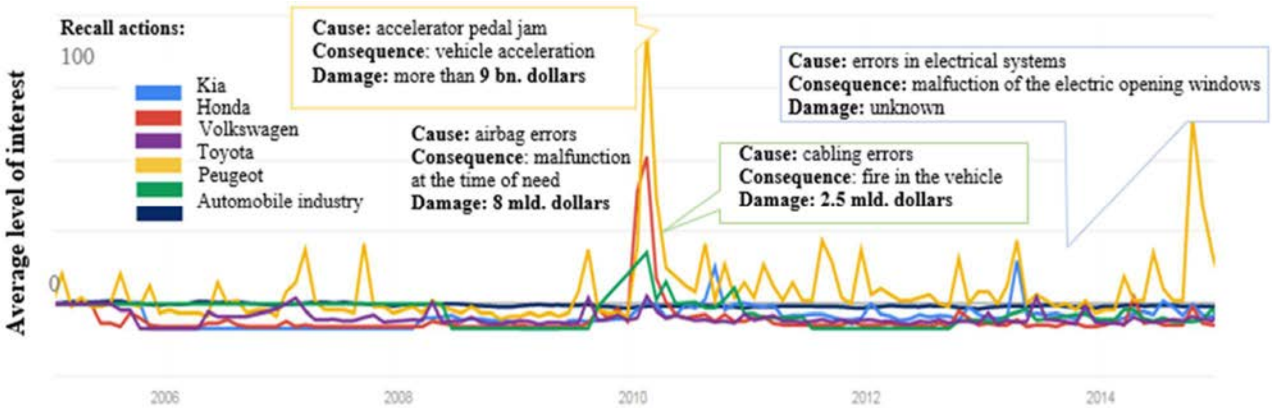

Figure 2 The interest of interested groups, source: own elaboration

Hypothesis H1 was confirmed.

Hypotheses (H2 –H5) were tested at user recall events that met criteria such as vehicle age, cost bearing, the standard length of repairs, the invalidity of the recall action, compensation in the event of an accident, inability to repair the vehicle. All these criteria have set limit values, which are listed in Table 2. During testing the hypothesis (H2), the risk analysis of the recall actions according to the assembly groups was used (Figure 2).

Hypothesis number 2 (H2):	***The quality of selected suppliers affects the quality of manufactured products.***

Based on a statistical analysis of the assembly groups of individual cars KIA, PSA, VW, the highest share of 26.35% was determined in electrical engineering and electronics, which represent the riskiest error of vehicles of these brands and therefore recall actions are necessary. The least risky error is the chassis 3.59% and other vehicle errors in the share of 25.75%. Based on the more precise analysis of the structure of recall actions of individual cars, it can be stated that electrical engineering and electronics has the highest share (34%) in the KIA car company. In other car manufacturers, it is at the level of 18-27%, specifically VW 18%, PSA 27%. Based on the overall assessment of errors, the highest proportion of errors in KIA is 5-34%, in VW at 7-18%, in PSA at 3-28%. Risk errors based on the analysis of errors in individual cars include electrical engineering, electronics and the brake system.

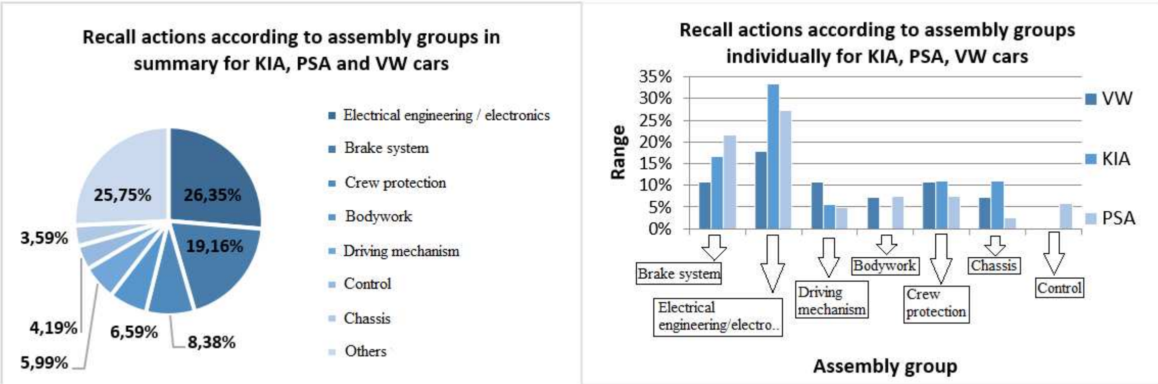

Figure 3 Analysis of recall actions by assembly groups, source: own research

Analysis of the causes of damage was used to test the hypothesis (H2) (Figure 3). The results of this analysis point to the causes of damage in selected car manufacturers in the sector of construction errors, which account for 38% of the total causes for calls. Other risk causes of vehicle damage are assembly errors at the level of 31%, material errors at the level of 14%, software errors at the level of 13%. Errors of assistance service and mechanical components range from 1.8-4%. In terms of approach to the causes of damage according to individual selected cars, it can be stated that in VW the causes in the sector of design error, material error, assembly error and software error are at the level of 10-32%, in KIA the causes of damage are oriented to the assistance service, design error, material error, assembly and software error in the range of 11-56%, in the car manufacturer PSA errors are mainly focused on design errors, assembly errors, software errors of 3-37%. The main cause of vehicle damage is structural errors, with which the KIA car company has a serious problem at the level of 56%. In conclusion, it can be stated that the biggest problem in the field of assembly groups is electrical engineering and electronics, in the field of causes of damage it is a design error. Based on both analyzes, it is possible to confirm significant deficiencies in the error rate at the KIA, in which electrical engineering represents 34% and design errors 56%.

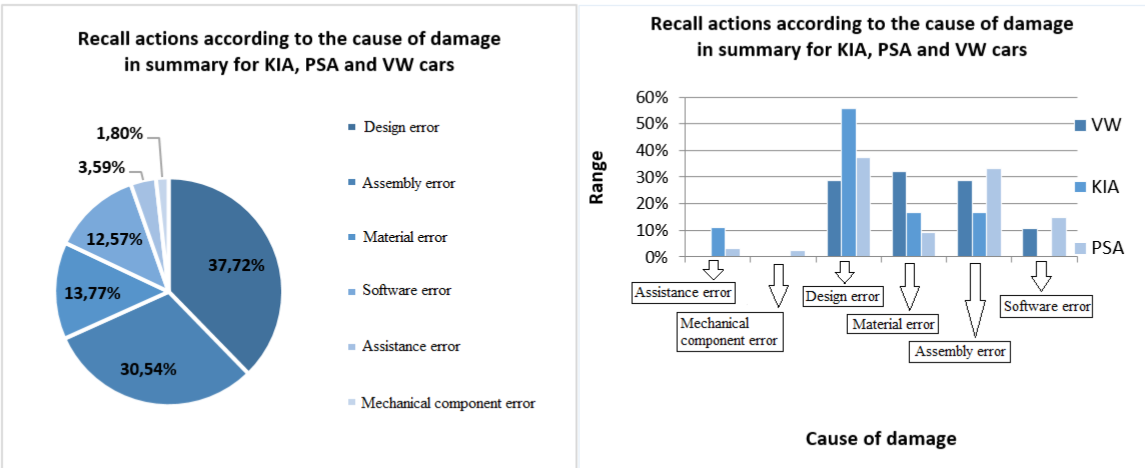

Figure 4 Analysis of recall actions according to the cause of damage, source: own research

Based on the analysis of risk factors of a selected group of automobiles in terms of assembly groups and causes of damage to vehicles, it was necessary to determine the risk of components in selected automotive companies and their relationship to the structure of supply companies for individual components. The results of this analysis indicate a high risk of components, but a small representation of suppliers for a given component. The average riskiness of components in the distribution network of the Slovak Republic reaches relatively low values: 0.60% -19.16%. However, this fact does not guarantee a reduced risk in the distribution network of supply companies for selected components. The critical area is the risk of brake components at the level of 20% with a low number of suppliers at the level of 4.53%. Based on the analysis, it can be assessed that to ensure the quality of the final production - vehicles, it is necessary for car companies to focus their attention on suppliers in the field of brake systems, as the number of suppliers in this sector is low and the risk is relatively high.

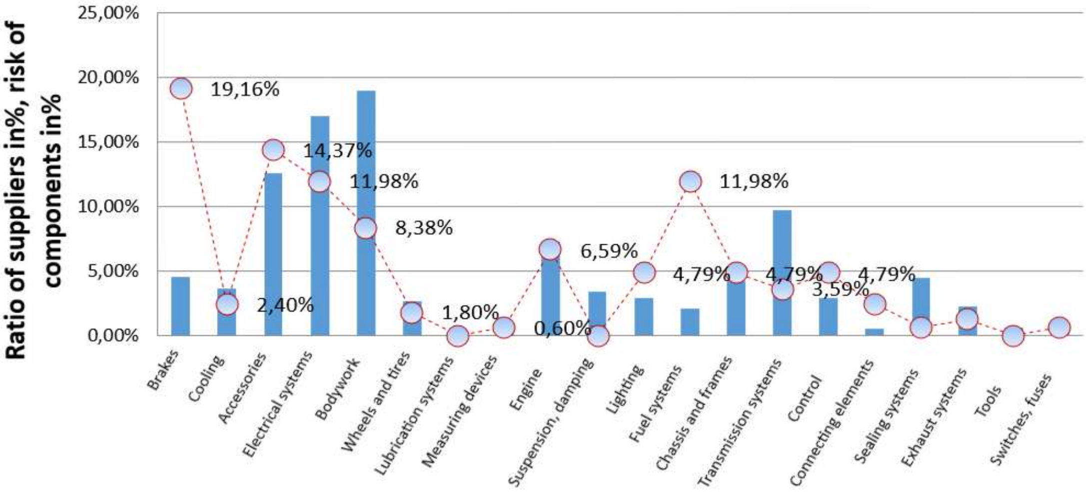

Figure 5 Comparison of the riskiness of components in the distribution network of the Slovak Republic, source: own research

In conclusion, it can be stated that the quality of selected suppliers does not affect the quality of manufactured products - vehicles.

Hypothesis H2 was not confirmed.

Hypothesis number 3 (H3):	**There is an indirect relationship between the number of calls to action and the probability of detecting errors.**

The highest average probability of detecting errors (Figure 5) is for Škoda (0.9993), Citroen and Peugeot (0.9992) vehicles. In contrast, for vehicles such as the Lamborgini, the probability of early error detection was lowest (0.9972). An analysis of the detectability of the error revealed that the most recall was recorded for Citroen and Peugeot vehicles, with the longest error detection time for Hyundai-Kia and Volkswagen Group brands. Overall, it can be confirmed that the number of recall actions, which was 890 333 vehicles, had a high average error detection rate of 0.999216212, but not the highest, which means that the number of called vehicles is not related to the probability of error detection, as declared by PEUGEOT, where 346 707 vehicles were called, but the probability of detecting errors was 0.999269888. This indicator was the highest for the Peugeot brand.

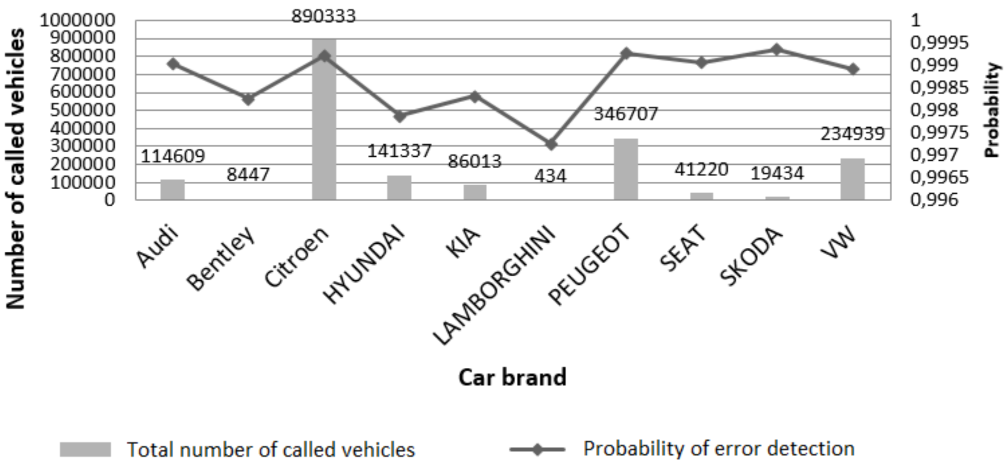

Figure 6 Error detectability analysis, source: own research

Hypothesis H3 was confirmed.

Hypothesis number 4 (H4):	**The pressure on accuracy and quality is directly proportional to the timeliness of error detection.**

During testing the hypothesis (H4), the analysis of the timeliness of the detection of defective components was used, which represents the optimal time of detection of the error on the vehicle and the implementation of corrective measures. The optimal period for detecting an error on vehicles is at the level of 3 - 11 years, which depends on several other factors, such as the year of manufacture of the vehicle, the number of recall actions and its beginning.

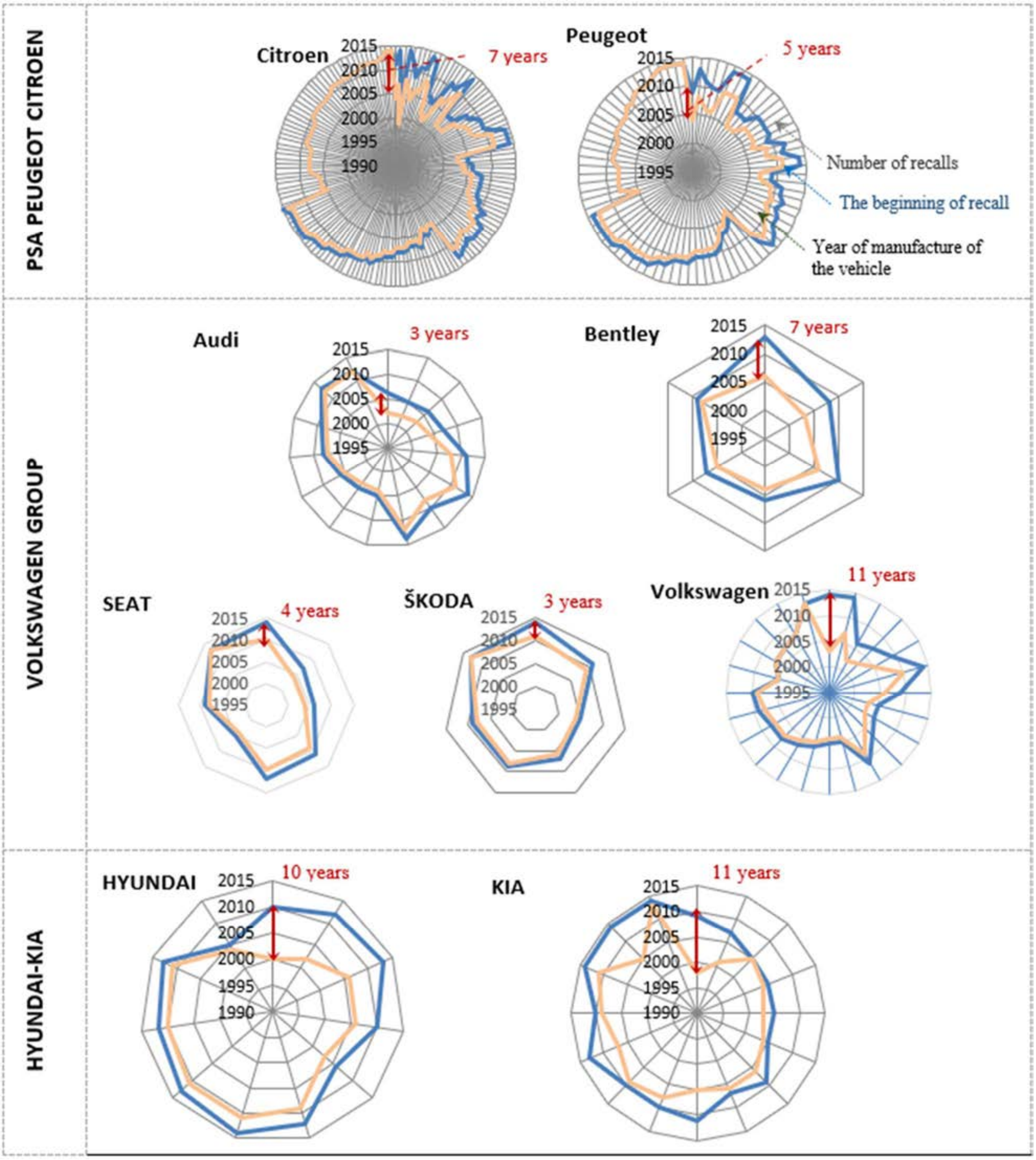

Figure 7 Error detection timelines, source: own research

Hypothesis H4 was not confirmed.

Hypothesis number 5 (H5)	**There is an indirect relationship between the error rate and the size of the risk.**

The relation between risk and error was monitored using the error rate indicator. Error rate calculation, resp. probability of error (Table 3), was obtained by dividing the sum of individual brands of called vehicles in the analyzed period by the sum of the total number of vehicles produced over the range of the period affected by the recall. Due to the mismatch of production capacity, only a relatively low error rate of Hyundai-Kia compared to PSA Peugeot-Citroen can be expected. These two car companies are relatively similar in terms of diversity and production volume, and they are relatively comparable. However, they cannot be compared with the car company Volkswagen Group, which significantly differs from the previous two companies in terms of production volume and diversity. The results show the lowest error rate in KIA with the lowest number of called vehicles.

Table 4 Error rate analysis and probability of error, source: own research

Company*(i)*	**Analysis period of call-to-actions** *(t)*	**Number of called vehicles** *(ZA)*	**Production period** *(n-m)*	**Number of manufactured vehicles** *(V)*	**Error rate** $F_i = \frac{\sum_{2005}^{2015} ZA_{ij}}{\sum_n^m V_{ij}}$
Hyundai-Kia	2005-2015	238 260	1998-2013	59 688 494	**0.399%**
PSA Peugeot Citroën	2005-2015	1 819 021	1999-2014	48 552 952	**3.746%**
Volkswagen Group	2005-2015	4 58 519	2002-2014	89 446 088	**0.513%**

Hypothesis H5 was confirmed.

As part of the research of recalls, we identified the dependence based on established hypotheses and evaluated the individual hypotheses as follows (Table 5):

Table 5 Evaluation of hypotheses of calling actions, source: own research

	Established hypotheses	**Interpretation**	**Rating**
H1:	There is a direct relationship between the growth of risk and the growth of stakeholder interest.	↑ risk = ↑ interest	✓
H2:	The quality of selected suppliers affects the quality of manufactured products	quality of deliveries = production quality	✗
H3:	There is an indirect relationship between the number of calls to action and the probability of detecting errors.	↑ frequency of errors ≠ ↑ error detection	✓
H4:	The pressure on accuracy and quality is directly proportional to the timeliness of error detection.	↑ accuracy = fast reaction	✗
H5:	There is an indirect relationship between the error rate and the size of the risk.	↑ error rate ≠ ↑ risk	✓

✓ Confirmed hypothesis, ✗ Unconfirmed hypothesis.

In the process of the testing hypothesis (H1), there is a direct relationship between the growth of risk and the growth of interest groups. The results of the hypothesis (H2) point to the fact that the quality of selected suppliers does not affect the quality of manufactured products - vehicles. Based on the overall assessment of errors, the highest proportion of errors in KIA is 5-34%, in VW at 7-18%, in PSA at 3-28%. The frequency of errors is inversely proportional to the probability of error detection. Risk errors based on the analysis of errors in individual cars include electrical engineering, electronics and the brake system. In terms of approach to the causes of damage according to individual selected cars, it can be stated that in VW the causes in the area of design error, material error, assembly error and software error are at the level of 10-32%, in KIA the causes of damage are oriented to the assistance service, design error, material error, assembly and software error in the range of 11-56%, in the car manufacturer PSA errors are mainly focused on design errors, assembly errors, software errors of 3-37%. The biggest problem in the sector of assembly groups are the items of electrical engineering and electronics, in the sector of causes of damage, it is a design error. To ensure the quality of the final production - vehicles, it is necessary for car companies to focus their attention on suppliers in the field of brake systems, as the number of suppliers in this sector is low and the ratio of risks is relatively high. There is no direct relationship between the error rate and the size of the risk. The number recall actions, which represents 890 333 vehicles, had a high average error detection rate of 0.999216212, but it is not the highest, which means that the number of called vehicles is not related to the probability of error detection, as declared by PEUGEOT, where 346 707 vehicles were called, but the probability of detecting errors was 0.999269888. The optimal period for detecting an error in vehicles is at the level of 3 - 11 years.

5 Conclusion

The recalls of products in the automotive industry represent an area of poor quality, which is reflected in the poor quality of components in automobiles, in the software, electrical, and electronic areas, in environmental quality, in management, and diagnostics. Based on the established hypotheses, the consequences and causes of the emergence of recall actions in automotive companies. The most common cause of recalls was found to be electrical engineering, electronics, and brake systems. At the same time, the risks associated with vehicle errors were identified. In terms of errors, these were design errors, material and software errors. The most called vehicles were Citroen, and the error rate was 3.74%. The greatest risk of the components in the supplier structure was represented by the car bodywork, electrical systems, and accessories. The biggest problem in the structure of suppliers was supply companies specializing in brakes, fuel systems, fasteners, lighting, and wheels. The error rate was used to monitor the relation between risk and error rate, and the results show the lowest error rate at KIA with the lowest number of called vehicles. The quality of selected suppliers does not affect the quality of manufactured products - vehicles. It is clear from the research results that the detectability of the error is not related to the number of called vehicles and the risk of components is not related to the structure and quality of suppliers to the automotive industry. Call-to-action is an effective tool for automotive companies to take corrective action and ensure the safety of customers who have purchased vehicles with potential, later identified errors. The error rate in the production process is a basic strategic goal of automotive companies, which is focused on reducing the error rate on the part of suppliers, reducing the error rate in the production process, and, ultimately, reducing the costs associated with call-to-actions.

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Measurement and analysis of the turning angle as an element of the course correction of an automated guided vehicle

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Abstract: Automated guided vehicles (AGV) are used at various stages of processing to carry out transport operations. Very often, they replace humans due to the monotonous or dangerous nature of the work. The use of AGVs requires special care in planning their routes so as to ensure an appropriate level of safety. Very often, AGVs on the designated route have planned turning and driving operations in corridors of a specified width. Many factors influence the correct and collision-free completion of the designated route. The article presents a measurement method and the experimentally determined angular deviation between the direction of movement realized before entering and after leaving the turn and the theoretically assumed one. Based on the determined angular deviations, the turning angle of the AGV was determined. It was assumed that the AGV vehicle moves along corridors of a specified width when negotiating turns. A statistical analysis was also carried out to examine the influence of the type of turn (left/right), vehicle speed and turning radius on the turning angle. The Kruskal–Wallis ANOVA test and the Mann-Whitney U test were used to analyze the study results.

1 Introduction

In industrial applications, AGVs are mainly used to automate internal transport in production halls or warehouses [1-4]. These activities help reduce operating costs and relieve employees from performing repetitive and monotonous tasks. AGVs contribute to increased reliability and repeatability of industrial processes and increased work safety. One of their advantages that makes most investors reach for AGVs is the fact that they don't require the installation of permanent infrastructure on communication routes. Therefore, they are used in situations that help avoid communication conflicts. They are most often used to supply production lines with raw materials, semi-finished products or to carry out warehouse operations. The lack of need to install permanent infrastructure is also of great importance when companies use rented halls because the transport system consisting of AGV vehicles can be easily moved in the event of a change of facility. It is advisable for industrial facilities equipped with AGVs to have wide corridors that will ensure the safety of employees and help reduce damage to products and equipment. However, wide corridors take up expensive space that could be used more effectively, for example, to accommodate additional devices or as storage space. Therefore, a very important issue when planning the AGV route is to determine the minimum required width of corridors for a given type of AGV. During transport operations, AGVs, e.g. when moving along designated corridors, must also perform maneuvers such as turns. This element of the AGV route is also very important because the AGV must overcome a specific turn within the physical limits of the corridor width.

The aim of this article is to present a method for measuring the turning angle and to investigate the influence of selected parameters on the turning angle of an AGV. The turning angle was calculated based on experimentally determined angular deviations between the direction of movement realized before entering and after exiting the turn and the theoretically assumed one. Data analysis allowed to determine the influence of the type of turn (left/right), vehicle speed and the radius of the turn on which the AGV moves on the turning angle.

The article is organized as follows. Chapter 2 presents a review of the literature on the navigation of AGVs and their application in intralogistics processes. Chapter 3 contains the characteristics of the research object and information on the applied measurement methods. Chapter 4 presents the statistical analysis of the experimentally determined turning angles and a discussion of the obtained results. Chapter 5 contains a summary and final conclusions.

2 Literature review

Various navigation systems are used to guide and determine the current position of AGVs, enabling the implementation of the designated route. An overview of the navigation approaches used is included in the works of [5,6]. The authors presented both classical AGV navigation techniques and heuristic navigation techniques as well as the application of artificial intelligence (AI) in AGV navigation techniques. At work [6] also noted that the latest research results indicate that combining, modifying and improving algorithms is the latest trend in efforts to improve AGV systems in navigation operations.

The basis for determining the current position in most cases is odometry. The authors of [7] reviewed the state of knowledge of the odometry methods used. This method of determining the vehicle position is burdened with many errors [8-11] and requires the use of additional measurement methods to correct the position [12-15]. Position correction can be performed continuously or cyclically, after a specific distance or after passing a specific marker – reference point [16-20]. Therefore, as noted by the authors of [7], most of the research in this area is focused on the types of sensors used together with odometry to determine the vehicle position, as well as the fusion and fusion of sensor data. Examples of such works are [21- 24]. In [21], a simultaneous localization and mapping (SLAM) algorithm based on a laser measuring system and encoders was proposed. In [22], an example of using vision sensors to track the AGV route was presented. The authors also applied fuzzy models in AGV navigation. In [23], the process of turning the AGV towards the target direction based on the information from the IoT sensor was presented. Many works propose methods using the fusion of several sensors. An example is the work [24], in which the authors used a multi-sensor fusion approach that integrates LiDAR, depth cameras, and infrared sensors for AGV navigation.

In addition to the above-mentioned works from the thematic areas of AGV navigation and the measurement methods and sensors used for this purpose, some researchers also focus their activities on the problem of AGV movement in narrow corridors or on performing specific maneuvers such as turns. Works devoted to this subject are no longer as numerous as research on AGV navigation in terms of the methods and sensors used. The authors of these works usually don't analyze the proposed methods in relation to a specific problem such as movement in a narrow environment or a turning maneuver. The tests they conduct concern the implementation of complex routes but without spatial restrictions for the vehicle. Research on a specific maneuver is very important because the actual trajectory that the vehicle follows differs from the assumed one. In the case of curvilinear movement, slippage of the drive wheels during movement on an arc results in failure to reach the assumed position. For further rectilinear movement in a limited space, e.g. a corridor, the angular deviation from the assumed direction of movement at the beginning of the rectilinear section after exiting the turn is very important. In the movement of a vehicle between the walls of a narrow corridor, the angular deviation from the assumed direction of movement may lead to a collision of the vehicle with the wall. In such cases, a very important issue when planning the route of the AGV is to determine the minimum required width of the corridors for a given type of AGV. An example of works in which the authors presented research results on collision-free planning and execution of movement trajectories are the works [25,26]. The authors of the first manuscript developed and implemented a trajectory controller based on predictive control for the problem of path tracking in narrow corridors. While in the work [26] the broadband localization technology was used. The problem of moving an automated guided vehicle in narrow corridors was also addressed by the authors of the manuscript [27]. They proposed a strategy for introducing a nonholonomic robotic wheelchair into a narrow corridor. To implement the proposed path planning, they used Augmented Reality (AR) markers. The route planning is performed using information about the position and attitude of the AR markers. Another work on the movement of AGVs in a narrow environment is [28]. It presents research results based on the use of the Pure Pursuit algorithm. The authors introduced a deep learning-based corridor area classifier, using 2D LiDAR data to select the appropriate localization system to solve the corridor effect. The problem of AGV movement in a narrow indoor environment was also addressed by the authors of [29]. In their case, the proposed method is based on a BLE beacon.

The presented solutions concern specific hardware and algorithmic solutions. The authors of these works didn't attempt to determine the factors influencing the movement parameters. Therefore, based on the conducted literature analysis, it was found that there is a gap in the study of AGV movement during the implementation of maneuvers such as turns and in particular in determining the parameters that affect the movement of the vehicle.

3 Material and Methods

The object of the research was an automated guided vehicle intended for transporting loads. The vehicle was set in motion and steered using two independently driven wheels. The tested object was equipped with an on-board computer, a set of data acquisition cards and appropriate control and measurement equipment. Due to the lack of flexible suspension, the vehicle was designed to move on smooth surfaces. The vehicle was built based on a three-wheeled structure with two driving wheels and one independent rotating one. The photo of the vehicle is shown in the Figure 1a.

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a) b)

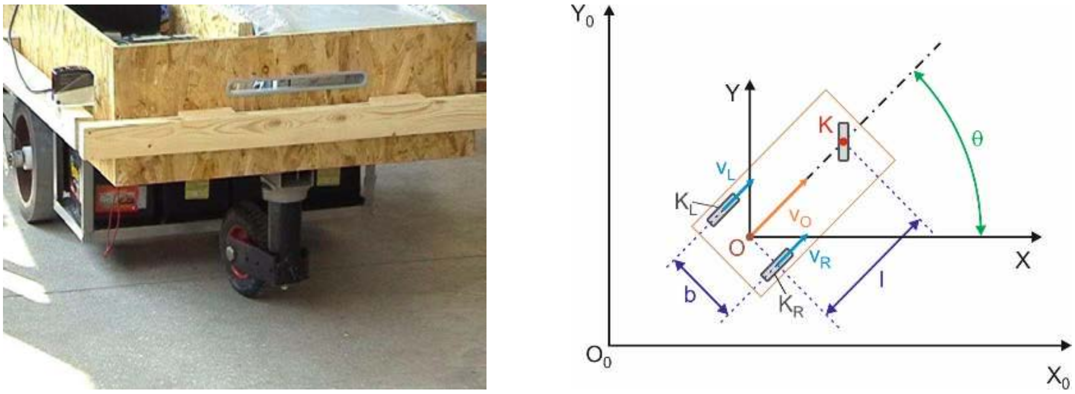

Figure 1 Research object – automated guided vehicle:
a) front view of the vehicle, b) AGV movement in the reference system $X_0O_0Y_0$

The vehicle, and in particular its tracking point K (Figure 1b) moved along given curvilinear trajectories. The tests included right and left turns with different constant radii and different constant speeds of the characteristic point O (Figure 1b).
At the beginning of a straight-line section, the traffic control system brings the vehicle to a given trajectory. Before starting the turn, the vehicle continued to move in a straight line for a distance of 4 to 9 m. The sections of straight-line motion after leaving the arc were of the same length.

After exiting the intended turn based on a 90º arc, the actual direction of the vehicle's movement was not perpendicular to the initial one. Laser rangefinders were used to determine the new direction of movement. This method involved measuring the distance from an assumed reference surface while the vehicle was in motion. Using laser rangefinders, the angular deviation of the vehicle's actual course from the theoretical course was determined in each case. This activity was performed both before the vehicle entered the turn and after exiting the turn. During the tests, left and right turns were made, the vehicle speed constants for a given test and the radii of the curves were changed. The diagram of the measurement method is shown in Figure 2.

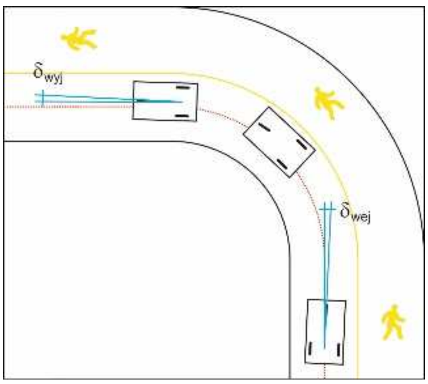

Figure 2 Scheme of the measurement method

Actual turning angle α_{turn}, by which the vehicle changed its direction of movement was calculated from the equations (1), (2):

$$\alpha_{turn} = 90^{\circ} - \delta \qquad (1)$$

$$\delta = (\delta_{out} - \delta_{in}) \qquad (2)$$

where: δ_{in} – vehicle deviation from the given direction of movement before entering a turn,
δ_{out} – vehicle deviation from the given direction of movement after exiting a turn,
δ – angular error.

In addition to parameters such as AGV speed, turning radius and type of turn (left/right), the turning angle is also influenced by the conditions of cooperation between the wheel and the road surface. Odometry was used to determine the position and generate a signal to control the operation of the drive motors. A constant wheelbase was assumed in the calculation program. This distance was determined in static conditions, assuming that it is the distance between the longitudinal symmetry planes of the drive wheels. At the wheel-road contact points located on these planes, there is no slippage during curvilinear motion of the vehicle. In actual operating conditions this distance is variable and the points where there is no longitudinal slip move left and right across the wheel width relative to the theoretical point.

In order to conduct the analysis, statistical tests were used to check whether the type of turn (right/left), AGV speed and turning radius had an influence on the turning angle of the AGV. For this purpose, the Mann-Whitney U test and the Kruskall-Wallis ANOVA were used. These are non-parametric tests and don't require assumptions about the normal distribution of a quantitative variable or the homogeneity of variance in the groups studied. The Mann–Whitney U test was used when two groups were compared in terms of a quantitative variable, while the Kruskal–Wallis ANOVA test was used when more than two groups were compared. The study was conducted at a significance level of $\alpha = 0.05$.

4 Results

The tests were conducted for 115 test drives performed by the AGV vehicle. During the recorded test drives, the vehicle made right and left turns at a speed of 0.2 m/s and 0.3 m/s with a turning radius of 2 m, 2.5 m and 3 m. Basic statistics were determined for the measurements performed and are summarized in Table 1

Table 1 Basic statistics obtained for the completed measurements

Parameter	Value
Number of measurements	115
Mean	89.5603°
Geometric Mean	89.5468°
Median	89.5992°
Minimum	85.1509°
Maximum	92.3941°
Lower quartile	88.2530°
Upper quartile	90.7479°
Standard deviation	1.5611°
Coefficient of variation	1.7431%
Skewness	-0.1891
Kurtosis	-0.6954

The average value obtained from the measurements is 89.5603°, the median of the analyzed set is 89.5992°. The minimum and maximum values from the analysed data set are 85.1509° and 92.3941°, respectively. The lower quartile has a value of 88.2530° which means that 25% of the recorded measurements are below this value, another 25% of the measurements have a value higher than 90.7479° (upper quartile). The standard deviation for the recorded measurements was 1.5611° which means that 2/3 of the measurements are between 87.9992° and 91.1214°. As part of the determined statistics, the coefficient of variation was also determined, the value of which is 1.7431%, which indicates low variability of measurement data. The skewness of -0.1891 indicates that most of the results have a value greater than the mean value of 89.5603°. A kurtosis of -0.6954 means that the values are clustered closer to the mean. This indicates that there are no outlier observations.

In the next stage, analyzes were carried out that allowed to determine the relationship between the turning angle and such parameters as the type of turn (left/right), the speed of the AGV, and the turning radius. The relationships that showed a statistically significant relationship $p < \alpha$ are presented in Table 2. These relationships were analyzed using the Kruskal–Wallis ANOVA test and the Mann–Whitney U test. Data were presented using a box-and-whisker plot because it best reflects the obtained results.

Figure 3 shows a box-and-whisker graph illustrating the differences in the turning angle depending on the direction of movement.

Table 2 Results showing the relationship between the turning angle and parameters such as the type of turn (left/right), AGV speed, turning radius

Variable	p
Turn type (right/left)	0.0000
AGV speed	0.0094
Turning radius	0.0309

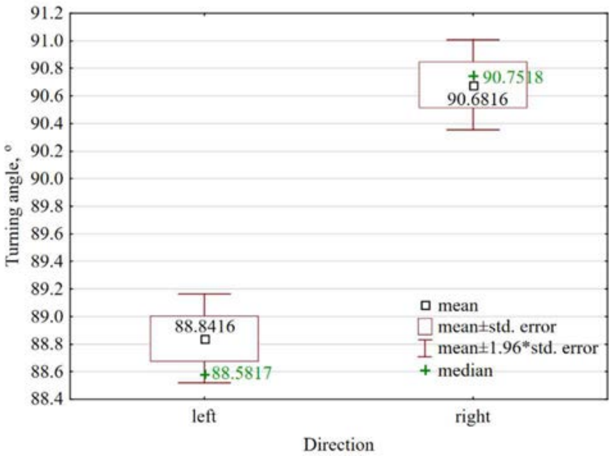

Figure 3 Turning angle vs. direction of movement

As can be seen in the graph (Figure 3), the mean (90.6816°) and median (90.7518°) of the turning angle of the AGV turning to the right are higher than the mean (88.8416°) and median (88.5817°) of the turning angle of the AGV turning to the left. In the case of an AGV turning to the right, the average and median values are higher than the assumed theoretical turning angle of 90°. Also the minimum value in the analyzed set is higher than 90°. However, for the turning angle when turning to the left, parameters such as the mean, median and maximum value in the analysed set take values below the assumed theoretical value of 90°.

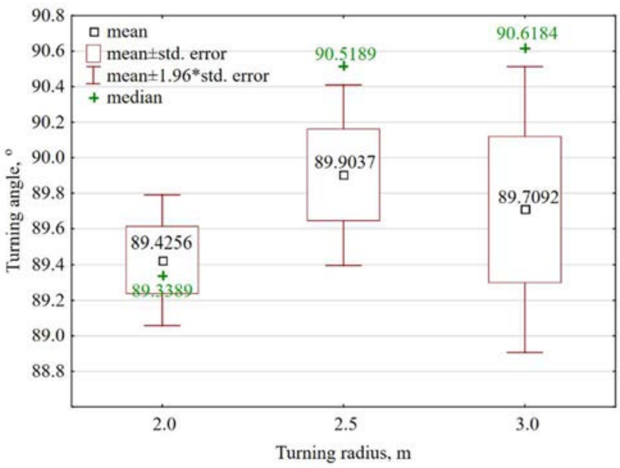

Figure 4 Turning angle vs. turning radius

Figure 4 shows the dependence of the turning angle on the turning radius value. The AGV performed turns with a radius of 2 m, 2.5 m and 3 m, respectively. As can be seen for a turning radius of 2 m the mean value of the turning angle and the median reached values below 90° and amount to 89.4256° and 89.3389°, respectively. In the case of measurements made for turning radius of 2.5 m and 3 m, the averages of these measurements also have values below 90°, amounting to 89.9037° and 89.7092°, respectively. The situation is different in the case of medians. For both the 2.5 and 3 m turning radius the median values are above 90° and are 90.5189° and 90.6184°, respectively. As the turning radius increases, it can be seen that the dispersion of the results increases.

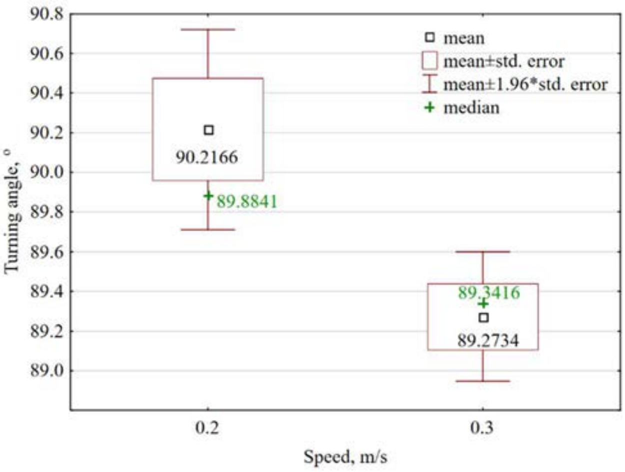

Figure 5 Turning angle vs. AGV speed

The graph in Figure 5 shows the relationship between the turning angle and the AGV speed. In the tests conducted, the vehicle moved at a speed of 0.2 m/s and 0.3 m/s. In the case of a speed of 0.2 m/s, the average value of the turning angle is above 90° and amounts to 90.2166°, while the median from the analysed set of measurements is below 90° and amounts to 89.8841°, respectively. For a speed of 0.3 m/s the average turning angle value and the median are below 90° and equal to 89.2734° and 89.3416°, respectively.

Figure 6 and Figure 7 show the interactions of parameters influencing the value of the turning radius.

Figure 6 presents graphs illustrating the simultaneous influence of the direction of movement and the AGV speed on the turning angle realized by the vehicle. As can be seen in the case of the turn to the left, the average values of the turning angle are similar and are 88.9987° for the speed of 0.2 m/s and 88.7808° for the speed of 0.3 m/s, respectively, their values differ by about 0.25%. In both cases, the turning angle values are below the theoretical turning angle value of 90°. However, in the case of a turn to the right, the difference between the average values of the turning angle is greater. The average value of the turning angle for a speed of 0.2 m/s is 91.6615°, while for a speed of 0.3 m/s it is 90.1399°, their values differ by more than 1.6%. Also in this case, a certain regularity can be noticed, namely, in both cases the values of the turning angle take values above the theoretical value of the turning angle of 90°.

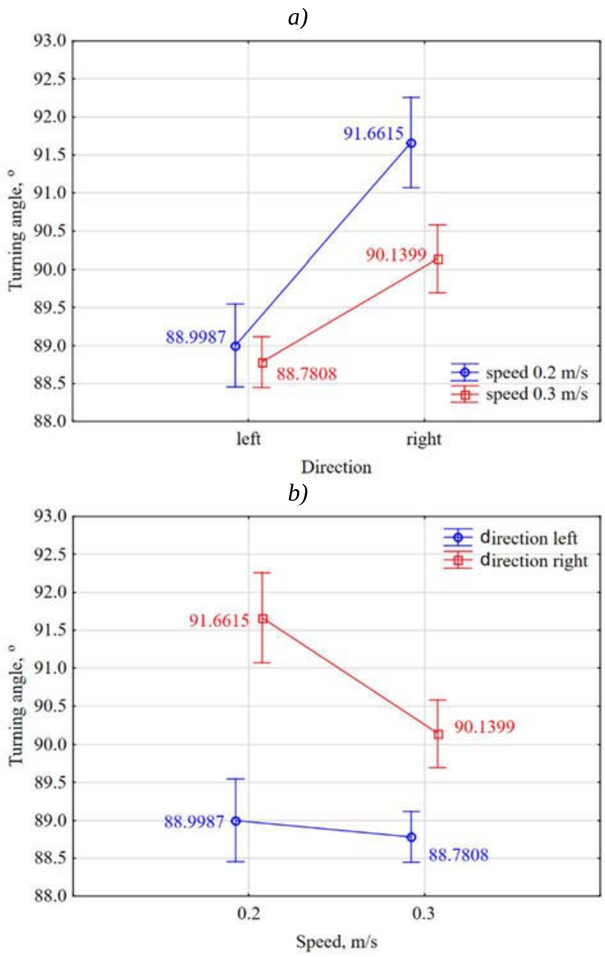

Figure 6 Interaction graphs: a) vehicle speed vs. direction of movement b) direction of movement vs. AGV speed

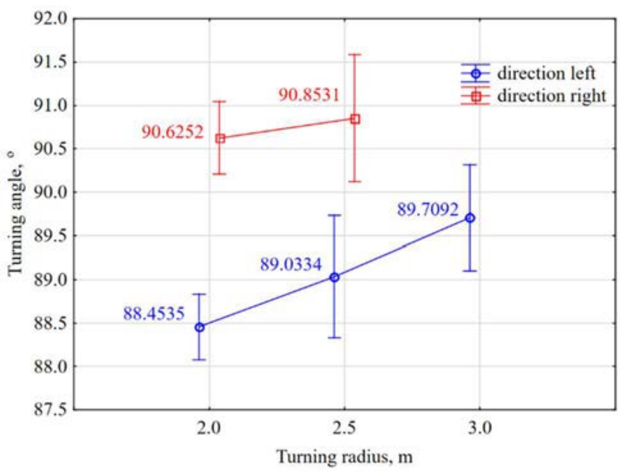

Figure 7 Interaction graph: turning radius vs. direction of movement

Figure 7 shows a graph showing the simultaneous influence of the turning radius and the direction of movement on the turning angle. In the presented graph it can be seen that the average values of the turning angle made in the left direction, regardless of the turning radius, take values less than 90° and are, respectively, for a radius of 2 m 88.4535°, for a radius of 2.5 m 89.0334°, and for a radius of 3 m 89.7092°. However, in the case of a right turn, the average values of the turning angle, regardless of the size of the turning radius along which the turn was made, take values above 90° and amount to 90.6252° for a turning radius of 2 m and 90.8531° for a turning radius of 2.5 m, respectively. Analyzing the simultaneous effect of the radius of the arc in which the turn was made and the direction of movement on the turning angle, it can also be seen that for the turn made to the left, the average values closest to the theoretical value were obtained for a turning radius of 3.0 m. It can be seen here that with the increase of the turning radius, the average value of the obtained turning angle is closest to the assumed theoretical value. However, in the case of turns made to the right, the opposite tendency was observed. As the radius of the arc along which the turn is made increases, the average value of the measurements performed increasingly deviates from the theoretical value.

5 Discussion

The analyses performed showed the relationship between the AGV speed, the turning radius and the direction of movement (left, right). They allowed for drawing the following conclusions:

- When analyzing the effect of the direction of movement on the size of the turning angle, it was noticed that for drives in which the AGV took a left turn, the turn angle was below 90°. However, in the case of a turn to the right, the turning angle took values above 90°. The results most similar to the assumed theoretical value of the turning angle of 90° were obtained for the turn to the right.
- Considering the influence of the turning radius the size of the turning angle, it can be seen that for the analysed turning radius the average values are very similar and are below 90°, while the medians for curve radii above 2.0 m have values above 90°. The results closest to the assumed theoretical value of the turning angle of 90° were obtained for a turning radius of 2.5 m.
- When considering the impact of the AGV speed on the turning angle, it was noticed that in the case of higher speed, both the average value of the measurements and the median were below 90°. In the case of an AGV speed of 0.2 m/s, the average value is above 90° and the median is below 90°. The results most similar to the assumed theoretical value of the turning angle of 90° were obtained for the turn performed at an AGV speed of 0.2 m/s.
- The simultaneous influence of several variables on the steering angle was also analyzed. It was concluded that the results most similar to the assumed theoretical value of the steering angle were obtained for the turn made to the right at a speed of 0.3 m/s.

Determining the dependencies listed above is particularly useful in practical applications of AGVs. These dependencies can be included in the developed algorithms for correcting the AGV course. Knowing them allows for introducing appropriate corrections in the algorithm and, as a result, collision-free implementation of the assumed task, which in this case is to perform a turn maneuver and enter a narrow corridor.

6 Conclusions

The use of the above measurement method and the analysis of the results will enable appropriate actions that will contribute to the increase in the accuracy of cornering movements.

Determining the impact of individual variables on the analyzed turning angle will allow to estimate the further movement of the vehicle. Knowing the values of the turning angle made under the impact of the factors considered, it is possible to determine at the assumed confidence level the minimum distance that the vehicle will travel after exiting the turn. Having determined from experimental tests the turning angle by which the vehicle's direction changed when taking a turn, it is also possible to estimate the wheelbase by means of numerical calculations using the recorded data from the encoders. Estimating the wheelbase value is very important because wheel base uncertainty is one of the two dominant odometry errors, next to wheel radii.

Knowledge of the individual dependencies as well as the ability to estimate the wheelbase allows for appropriate corrections to be made in the AGV navigation algorithm.

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Suppliers re-evaluation for tomorrow's smart supply chain: AHP approach and performance criteria in automotive industry

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Keywords: automotive industry, intelligent supply chain, supplier re-evaluation, quality, case study.
Abstract: The automotive sector has seen significant growth in recent years, with supply chain management becoming a key pillar for meeting evolving industry demands. Effective supply chain management relies heavily on material handling, impacting both inbound and outbound logistics. The study addresses the issue faced by automotive clients experiencing a decline in their quality KPIs due to non-compliant products delivered by suppliers. The focus is on identifying these suppliers, reclassifying them based on performance, and establishing key criteria for supplier re-evaluation, to address quality issues. We identify eight critical supplier selection criteria in the automotive sector. Supplier failures can lead to non-compliant raw materials, causing customer complaints and warranty returns due to undetected defects. The second part of the study involves reclassifying the suppliers of an automotive company with deteriorating quality KPIs. Using the Pareto principle and Lorenz curve, we identified the suppliers responsible for the majority of raw material deliveries. The Analytic Hierarchy Process (AHP) was used to reclassify suppliers based on quality criteria. The reassessment allowed us to identify underperforming suppliers who needed corrective action plans, or in some cases, exclusion in favor of suppliers meeting industry standards. This process involved meetings with the company's management team to define effective action plans aimed at improving quality performance. This approach will help automotive companies better align their supply chains with market demands, delivering value to customers while maintaining competitiveness. By optimizing supplier selection and reclassification, companies can reduce complaints, improve satisfaction, and enhance both the customer experience and production efficiency.

1 Introduction

Supply chain management is an essential part of the business strategy of many automotive companies [1], directly influencing their ability to meet customer demand, minimize costs and maximize customer satisfaction by reducing or eliminating complaints through the delivery of compliant products.

Nowadays, automotive organizations aim to introduce the smart supply chain of tomorrow as a crucial lever of development for this sector, but the constraint is to produce products with high quality in order to satisfy the customer and having an objective of zero claims. This is why automotive companies try to improve their chain weather inbound, intern and outbound logistics for the production management flow.

Inbound logistics plays a crucial role for the automotive industries. Therefore, any disruption at suppliers' companies can cause different types of anomalies at the customer such as: delivery of non-compliant products, delivery in delay, non-compliance with the quantity requested to be delivered or delivery of erroneous items, confusion of either references or products for another customer, etc. All this has a direct impact on the performance of the customer's supply chain, and consequently the disruption of the production lines of end customers or even the shutdown of the customer's supply chain, as a result the dissatisfaction of the consumer for the product.

In this context, the automotive industries in Morocco and even around the world have recently experienced major disruptions in their supply chains, since the Covid-19 pandemic in 2019/2020. Emphasizing the problem of industries that produce electronic cards. This issue has disrupted any industry in the world that has as a component in the nomenclature of the product to manufacture an electronic card, more mainly the automobile markets that have experienced several successive shutdowns and technical unemployment of their collaborators and employees.

At the heart of this effective management is supplier selection and re-evaluation, a strategic decision that can have a significant impact on the overall performance of tomorrow's intelligent supply chain. The aim of our study is to identify the key criteria for the selection and re-evaluation of supplier performance, addressing the issue faced by automotive clients who suffer from a degradation of their quality KPI due to the non-compliance of products delivered by suppliers. This paper underscores the need to regularly re-evaluate the supplier panel in these situations to implement corrective actions or even replace suppliers if necessary, focusing on essential performance criteria needed to choose suppliers for an efficient and intelligent supply chain. In this article, we take a detailed look at supplier selection criteria, highlighting the key factors to consider as fact ensures supply chain success. This is followed by a case study of an automotive multinational industry well placed to reclassify its textile suppliers assumed the deteriorating quality situation caused by non-compliant raw materials received from suppliers. The study will begin with an illustration of the purchasing panel of suppliers working with this multinational and then based on the number of items to be delivered by each supplier; it will be easy to target the niche of suppliers to be included in the study applying the Pareto principle validated by the Lorenz curve.

Moreover, by applying the AHP method in multi-criteria decision making with its four steps (identification of evaluation criteria, comparison matrix, calculation, and the last step evaluation.), we will be able to determine the most appropriate supplier for the project[2]. Also deciding which suppliers to carry on working with and which ones to turn around so as not to lose customers and keep their loyalty.

2 Literature review: supplier selection criteria and re-evaluation

When we talk about supply chain management, in literature many articles treat the topic in high level considering the issue of evaluation and selection supplier as the first essential step for companies in order to improve their visibility in the market regarding customer's satisfaction. Moreover, industries aim to attract new projects for more gain. While reviewing multiple papers, no article handles the subject in retroactive face by re-evaluating the purchasing panel of an industry emphasizing a problematic experienced in that company, also making an update by criteria for smart supply chain of tomorrow to optimise Keys performance indicators, so this let our study newer and unique.

Many authors and studies take the subject of supplier selection like a priority in research. For textile industries [3] the process present 3 phases: phase 1 supplier selection with 7 criteria that have an impact to identify qualified suppliers, then phase 2 proposes 8 criterions to explore if the supplier selected meet what is required in the products and which level. the third and final phase. Supplier re-evaluation with 9 criteria, it examine the performance of system for suppliers included in the selection process [4].

Nowadays, the automotive industry worldwide is booming, with many variations. So that, in the automotive industries purchasing team should integrate a crucial element, while selecting and evaluating suppliers by different multicriteria [2], considering the procurement strategy one supplier for many products , so called the product life cycle of each product (PLC) [5], and for the case of automotive industries tier 1 it's necessary to highlight that the reputation of suppliers is vital element to be considered [6].

In terms of supplier selection, there is a wide range of criteria and methods that has been studied to assist organizations in identifying the best suppliers and in improving their supply chain performance [1,7]. According to recent literature reviews on the state-of-the-art in supplier selection frameworks, both traditional criteria (cost, quality and delivery time) as well as green or sustainable criteria are considered in most of these frameworks, particularly those from industries that stress environmental considerations [2].

Four basics criteria founding from Fuzzy-AHP method in decision making : "Environment management system', 'Pollution control', 'Quality', and 'Green image in order to select green suppliers in the automotive industry [8].

Multi-Criteria Decision-Making (MCDM) Methods: MCDM methods such as Analytic Hierarchy Process (AHP), Data Envelopment Analysis (DEA), fuzzy logic models are regularly used for providing a weight to the supplier aspects and supporting the selection decision under some circumstances. Such approaches manage a trade-off between quantitative and qualitative aspects, allowing for performance metrics efficiency (e.g., CO2 emissions), while still considering environmental criteria [9].

Green Supplier Selection: An expanding domain of supplier selection research addresses green or sustainable criteria, where suppliers are selected based on the environmental impact and efficient utilization of resources. This includes aspects such as carbon footprint, waste disposal, and sustainable practices. This integration of these criteria is viewed as fundamental for industries including manufacturing and construction, which face rising demands to limit their impacts on the contentment with the environment [10].

Ontology-Based Knowledge Management to overcome fragmentation in this domain, certain research works propose ontology-based frameworks to specify knowledge and support decision-making. This method systematizes criteria and selection methods, facilitating easier comparisons as well as the diffusion of information between firms [11].

New Trends and Research Directions: The review also provides insights into addressing challenges like reconciling economic and green criteria, compensating for uncertainties in the supply chain level, as well as integrating real-time data that underlies continuous re-evaluation of suppliers. Future research, we suggest, may integrate AI and ML more deeply to enhance adaptability and predictive capabilities in selecting suppliers and re-evaluating ones [10].

These findings highlight the importance of continuing to evaluate and reassess suppliers as organisations work to meet efficiency, regulatory and sustainability pressures.

3 Methodology

The present article analyzes the impact of re-evaluating purchasing panel in the automotive industry to improve and rectify the quality KPI for each automotive company suffer from non-conformity of products delivered by suppliers [12]. For this purpose, a case study in the sector will affect positively our analysis; the preselected suppliers were analyzed in correlation with the AHP method [13]. Adding that the performance indicators of each industry are affected by the supplier selection flow to define a purchasing panel, in particular the selection criteria phase, which must be precise and concise to achieve an intelligent supply chain. Considered criteria evaluation for suppliers were determined according to a survey of experts in this automotive sector. The criteria defined requires organizations to assess their suppliers preselected after knowing any deviations in the targeted KPI, keeping in mind driven customer satisfaction as a pillar ensuring quality approach.

Faced with industry demands, automotive experts have developed a comprehensive set of criteria for supplier selection, to be followed by each organization according to its problematic issue seeking to resolve.

This paper takes the AHP method and key criteria selection for supplier evaluation and selection in automotive industry based on characteristics of product quality/conformity to provide a systematic reassessment of suppliers and identify the steps to be taken for an intelligent supply chain, the methodology is designed in multiple phases. The objective of this study is to provide the key criteria selecting automotive suppliers, in the other hand realize the suppliers who need improvement or corrective action towards quality and compliance requirements for automotive industry. Based at first, on a survey aimed to identify the key criteria for supplier selection in the automotive sector to build a smart supply chain. The target audience included various automotive suppliers, members of the management committee within the studied industry ;(comprising 2,300 employees operating 24 hours a day, 6 days a week in three rotating shifts), as well as the industry's clients and automotive experts. The survey followed a qualitative design and utilized a mix of question types, including open-ended questions, Likert scales, and multiple-choice formats. The survey medium varied: face-to-face interviews, paper surveys, and verbal surveys conducted via calls were employed. In total, we collected 500 samples over a six-month period. To ensure participant trust, we guaranteed data confidentiality by anonymizing all responses. For paper surveys and email-based distribution, regular reminders were sent to participants to maximize response rates. During the data analysis phase, the collected responses were systematically organized in an Excel document. The analysis focused on identifying satisfaction scores and common feedback themes. This process allowed us to extract the required criteria in relation to the automotive industry that are: Product or service quality, cost prices and costs, Terms of delivery, Production capacity and stock availability, Customer service and technical support, Innovation and R&D, Financial stability and reputation and finally Sustainability and social responsibility.

Secondly, in difficult suppliers we wanted to prioritize selection actions and provide a proper recovery plan using AHP approach. In this part of research, we use quantitative methods using the Pareto principle to choose the suppliers from the purchasing panel requiring the focus. In addition, to confirm our Pareto analysis, we used the Lorenz curve, to see the distribution of items among the different suppliers, which enabled us to analyze their concentration and visualize them, while quantifying inequality by calculating the Gini coefficient. The AHP method which allows structuring complex decision problem and the systematic comparison of many criteria; this method was used to re-evaluate the supplier performance, based on 4 criteria according to the survey which data that was collected through a questionnaire given to a sample of suppliers and experts in the automotive industry as explained in the first part. The analysis was complemented by data from supplier audit reports, sources of previous evaluations and historical data in databases. The data was then collected and incorporated into an AHP model, on which the weight of each criterion in terms of importance for supplier selection has been determined. The AHP method was used to rank suppliers according to their overall performance, taking into account the strategic priorities of automotive companies. Suppliers with low scores were identified as requiring a recovery plan or, in the most serious cases, replacement.

Apart from that, although the AHP method is well known for its authenticity, it uses subjective judgments in defining weights, which sometimes can create bias into the results as a limitation of this study. Supplier re-evaluation is a multi-criteria decision-making problem where many factors have to be considered at the same time; therefore, the AHP method should be used. It also facilitates the systematic and streamlined decision- making; the Figure 1 represent the Methodological Framework for the Study: Re-evaluating Suppliers in the Automotive industry.

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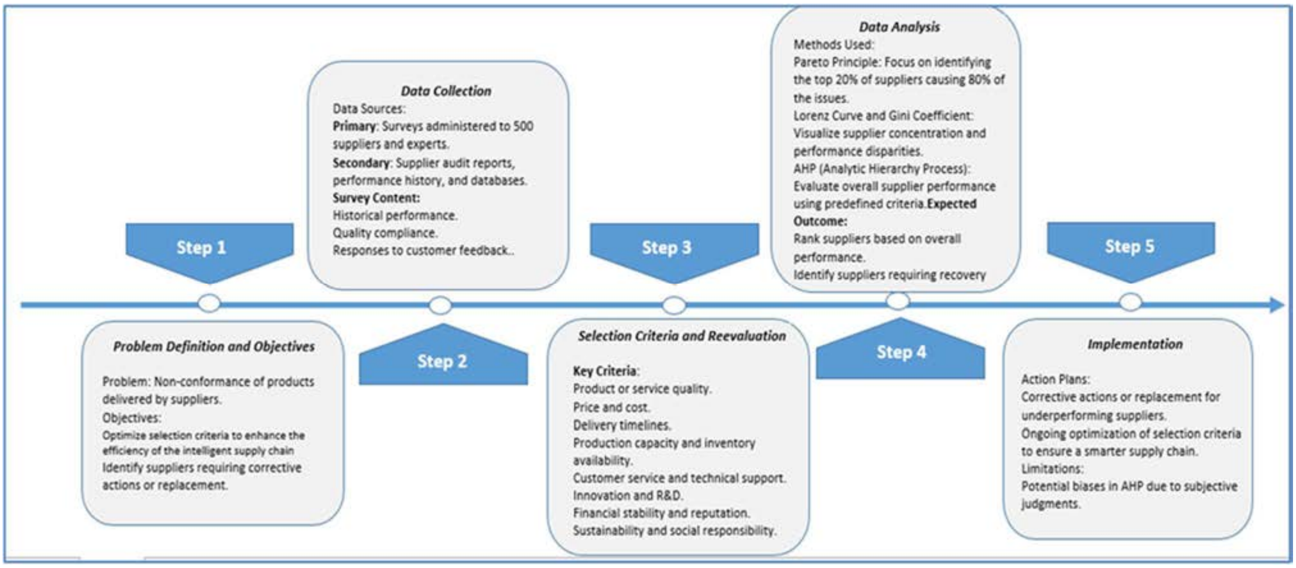

Figure 1 Methodological framework for the study: re-evaluating suppliers in the automotive industry

4 Results and discussion

4.1 Result analysis: Supplier criteria selection and reclassification for the automotive industries

According to a survey includes a population of 500 suppliers, customers and experts in the automotive sector, the following criteria in Table 1 are the keys for the issue of supplier selection, re-evaluation and reclassification leading to a smart supply chain of tomorrow for automotive industries.

Table 1 Supplier selection criteria

Criteria	*Points to highlight*
Product or service quality	Industries seeking to have a good relationship with their customers by offering to them compliance of products that meet established quality standards [8]. Therefore, the quality of products delivered by a supplier remain a crucial point to ensure, through looking for suppliers who may provide products that meet customer's expectations.
Prices and costs	The price of the products or services delivered by a supplier is a fundamental criterion in the selection process. Considering if the cost of products is jusfied by the quality provided at supplier's company.
Terms of delivery	Providing products on time is one of the most important criteria for automotive industries, any delay conducts many disruptions in customer's lines arrived to consumers.
Production capacity and stock availability	The agreed delivery supplier relies on his capacity production, adding the importance of stock availability at supplier for any issue facing whether it is at the customer or the supplier.
Customer service and technical support	Customer satisfaction ensured by the creation of good interface supplier-customer team, in order to respond to customer's complaints and problematic. In addition, supplier should offer support to technical customer's issue.
Innovation and R&D	Having a center of research and development for a supplier will increase the opportunity to be selected, because the supplier has the ability to invest and innovate in the products.
Financial stability and reputation	This criterion related to the reputation and the image of that supplier industry in the market and if he is financially stable. So that the customer's avoid non-conformity of products either the stoppage of supplier production lines.
Sustainability and social responsibility	In recent times, industries have taken the direction of taking into account different ethics standards and social responsibility in their world of employment and hoping to have them in their customers: such as the environmental aspect [7], the human aspect, working conditions [14,15], automotive certifications...

4.2 Result analysis: Case study of supplier reclassification for textile raw materials in the automotive industry

4.2.1 Background

In the context of the reclassification of suppliers included on the company's purchasing panel, a specific study had to be carried out. In this study, we seek to pinpoint the suppliers with the greatest impact and the most effective ones in order to remedy the quality situation, which had deteriorated due to customer complaints linked to the non-conformity of textile raw materials [4], which appeared only after delivery and integration of the products delivered into the customer's production chain.

Table 2 displays the purchasing panel of this multinational automotive company, which exceeds 520 items spread over several suppliers, keeping the names of supplier's manufactories confidential for reliable results.

Table 2 Supplier panel

Supplier	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
Number of items	96	61	52	36	33	26	23	20	18	17	14	13	12	12	12	8	7	7	6
Supplier	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33	F34	F35	F36	F37	F38
Number of items	5	4	4	3	3	3	3	3	2	2	2	1	1	1	1	1	1	1	1
Supplier	F39	F40	F41	F42	F43	F44	F45	F46	F47	F48	F49								
Number of items	1	1	1	1	1	1	1	1	1	1	1								

4.2.2 Choice of suppliers to include in the study

Pareto's law , Lorennz curve

The Pareto principle (or law) is an analytical tool born of the empirical observations of the economist Vilfredo Pareto and the qualitician Joseph Moses Juran, who disseminated the concept in 1954 [16,17].

The Pareto principle is a general method for separating any aggregate into two parts: vital problems and more secondary problems - in all cases, the application of the Pareto principle makes it possible to identify the properties of strategic problems and to separate them [16].

For Juran, this principle has "universal" value: The fact that managerial problems generally have the same properties makes the Pareto principle a universal tool for analysis [16]. In short, the Pareto principle, also known as the 80/20 principle or the 80/20 law [18,19], describes a rule according to which 80% of the effects are the product of 20% of the causes [17].

In fact, applying the Pareto law 20% of suppliers deliver 80 % items the study will be based on suppliers, who deliver 12 and more items to this multinational automotive industry as depicted in Figure 2. As a next step, to validate our Pareto analysis result, we'll approach the analysis of item concentration by supplier, with Lorenz curve plotting [20], in order to rank suppliers first in ascending order by number of items delivered. A subsequent calculation of the cumulative percentage is carried out for suppliers and items, as abscissa and ordinate axes. The origin (0,0) is shown as the first point, and the last point (1,1) represents the total distribution. In order to quantify the distribution inequality, we calculate the Gini coefficient using the following formula (1):

$$Gini\ coefficient\ = 1-(2*area\ under\ the\ Lorenz\ curve) \quad (1)$$

While the area under the Lorenz curve is calculated using the trapezoidal method, the area of the trapezoid between two successive points (X_{i-1}, Y_{i-1}) and (X_i, Y_i) , X_i for the cumulative percentages of suppliers and Y_i for the cumulative percentages of items. Finally, by summing the areas of the trapezoids between all successive points we get the total area under Lorenz curve [20]. Given by the following formulas (2) and (3):

$$trapezzoid\ area = \frac{(Y_{i-1}+Y_i)}{2}.(X_i - X_{i-1}) \quad (2)$$

$$area\ under\ the\ Lorenz\ curve\ = \sum_{i=1}^{n} \frac{(Y_{i-1}+Y_i)}{2}.(X_i - X_{i-1}) \quad (3)$$

- X_i the cumulative percentages of suppliers attending the point i,
- Y_i the cumulative percentages of items attending the point i,
- n total number of suppliers.

When we apply the previous steps, we get as a result of the calculation (4):

$$Gini\ coefficient\ = 1-(2*area\ under\ the\ Lorenz\ curve) = 1-(2*0.16) = 0.68 \quad (4)$$

The Lorenz curve represented in Figure 3, and our calculations give a Gini coefficient of 0.68, which indicates a very unequal distribution of items among the suppliers. Since the Gini coefficient ranges from 0 to 1, a result close to 0 suggests a more equal distribution, while a result close to 1 indicates a high concentration [20]. For our study, a minority of suppliers holds a significant share of the items (15 suppliers out of a total of 49 suppliers).

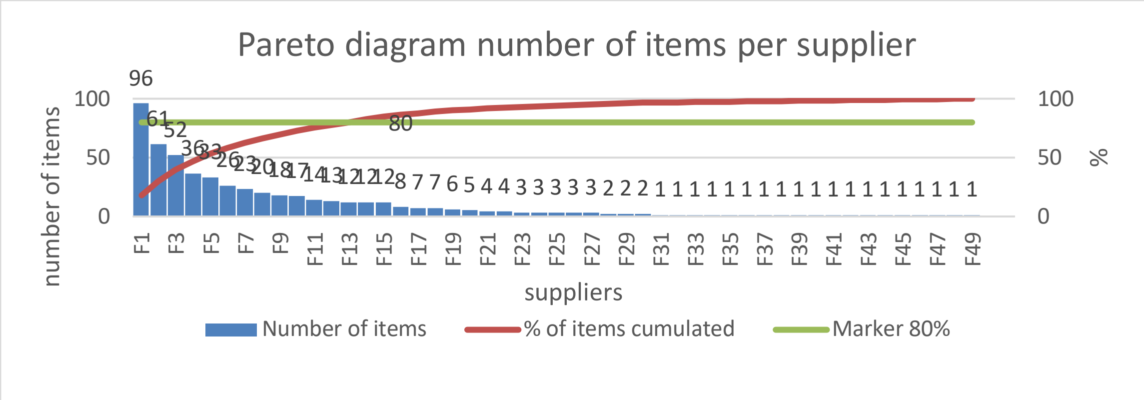

Figure 2 Pareto diagram

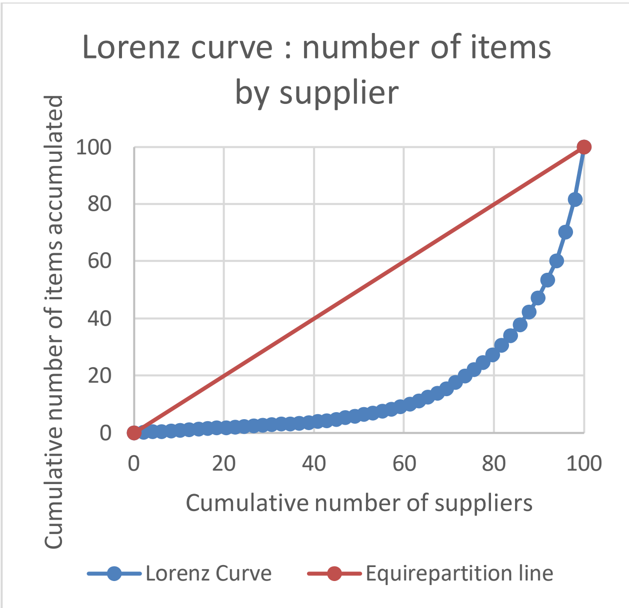

Figure 3 Lorenz curve

4.2.3 Application of AHP method

Whhy using the AHP method

One of the most widely used decision support methods; the AHP method was designed by Thomas Saaty (1977, 1980) in the 1970 [21]. Since its introduction 40 years ago, it has been used in a wide range of applications all over the world [22-23].

Using the AHP approach, a model composed of a hierarchy of criteria is developed with the aim of evaluating the alternatives considered for achieving a specific objective [24]. Implementing AHP involves the representation of a decision problem by a hierarchical structure reflecting the interactions between the various factors (objective, criteria and alternatives) of the problem [13].

Identification of assessment criteria

In order to remedy the quality situation, the study will focus on the following evaluation criteria [25] in Figure 4. In this paper, we mean by each criterion seeking improvement of quality for this automotive industry:

Product or service quality: number of complaints related to each supplier over 6 months.

Customer service and technical support: On-time response to complaints (D3 24 hours, D6 15 days, D8 60 days).

Production capacity and stock availability: quantity produced per week and availability of stock items in the event of non-conformities.

Innovation and R&D: Availability of a development centre or engineering team

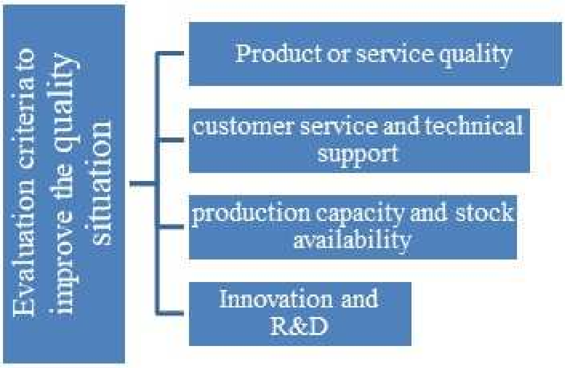

Figure 4 Supplier evaluation criteria

Comparison matrix

In the AHP process, the relative importance or weight of the criteria is established through expert consultations, interviews, or group discussions [26,27]. Each criterion is compared with the others in pairs, using either qualitative or quantitative evaluation methods [27], nine-point numerical scale, known as the Saaty scale, is commonly used for these pairwise comparisons. The details of this scale are presented [28], in Table 3 below:

Table 3 Saaty scale

Importance intensity	Definition	Explanation
1	Equal Importance	Judgmental or need
3	Moderate importance of one over another	Judgmental or need
5	Strong importance	Judgmental or need
7	Very strong importance	Judgmental or need
9	Extreme importance	Judgmental or need
2, 4, 6, 8	Intermediate value between the two adjacent	Judgmental or need

For the AHP comparison matrix, the relativity importance of the criteria is defined using Saaty's scale. Each important criterion i in relation to a criterion j, and this is done by pairing each position (i,j), and for each value of (j,i)th position of the matrix will be the inverse of the value attributed to (i,j)th position according to the equation (5) [27]. Therefore, to ensure this first step, consultation with the Purchasing Manager, the Director and the Quality team within the company was essential in order to set the comparison coefficients for each pair of criteria according to the Saaty scale [29]. It is vital that the purchasing and quality managers, and possibly their colleagues, are involved at this stage, as they are in the best position to assess the relative importance of each pair of criteria [30].

$$a_{ij} > 0, \quad a_{ji} = \frac{1}{a_{ij}}, \quad a_{ii} = 1 \; \forall i \qquad (5)$$

Where each element a_{ij} is the priority ratio between the criterion i and criterion j according to a preference scale. The matrix of all the coefficients is presented in the form of Table 4.

Table 4 Comparison matrix

	customer service and technical support	Quality of product or service	production capacity and stock availability	Innovation and R&D
customer service and technical support	1	(1/5)	(1/3)	(1/5)
Quality of product or service	5	1	2	2
production capacity and stock availability	3	(1/2)	1	3
Innovation and R&D	5	(1/2)	(1/3)	1

Weight of evaluation criteria

Once the comparison matrix step accomplished, we should now obtain the weight of each criterion. Therefore, we will use the geometric approximation method [31] to calculate the eigenvectors making up the estimation vector. This is done by applying the nth root equation (where n is the size of our comparison matrix, which is 4) of the product of the elements in each row of our comparison matrix following the equation (7). At the end, each element of the estimation vector obtained is divided by the sum of all the elements of this vector: this is the normalization step, to obtain the relative weight of each criterion.

Step 1: Apply the power $\frac{1}{4}$ to each element of the matrix A by the equation (6):

$$A^{(\frac{1}{4})} = \begin{pmatrix} 1^{(\frac{1}{4})} & \frac{1}{5}^{(\frac{1}{4})} & \frac{1}{3}^{(\frac{1}{4})} & \frac{1}{5}^{(\frac{1}{4})} \\ 5^{(\frac{1}{4})} & 1^{(\frac{1}{4})} & 2^{(1/4)} & 2^{(\frac{1}{4})} \\ 3^{(\frac{1}{4})} & \frac{1}{2}^{(\frac{1}{4})} & 1^{(\frac{1}{4})} & 3^{(\frac{1}{4})} \\ 5^{(\frac{1}{4})} & \frac{1}{2}^{(\frac{1}{4})} & \frac{1}{3}^{(\frac{1}{4})} & 1^{(\frac{1}{4})} \end{pmatrix} \qquad (6)$$

Step 2: Multiplying the elements in each row of our matrix $A^{(\frac{1}{4})}$: The product of the elements in line i equation (7):

$$A1_i = P_i = \prod_{j=1}^{n} a_{ij}^{(\frac{1}{4})} \quad (7)$$

Step 3: Sum of line products application of the equation (8):

$$A2 = S = \sum_{i=1}^{n} A1_i \quad (8)$$

Step 4: Calcul the relative weight of each criterion following the equation (9):

$$w_i = \frac{A1_i}{A2} \quad (9)$$

Table 5 Weight of evaluation criteria

	A1	A2	w=Weight=A1/A2
customer service and technical support	0.3398	4.8665	0.0698
Quality of product or service	2.1147	4.8665	0.4346
production capacity and stock availability	1.4565	4.8665	0.2993
Innovation and R&D	0.9554	4.8665	0.1963
Total	4.86647		

Before moving on to the evaluation stage by calculating the score for each supplier, it is essential to calculate the CR Consistency Ration, to check the consistency of our judgments on our comparison matrix, calculated as the followed equation (10) :

$$CR = \frac{CI}{RI} \quad (10)$$

With CI the consistency index to calculated we should use the equation (11) below :

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (11)$$

Where n is the size of the matrix and λ_{max} maximum eigenvalue of each criteria in the matrix.

For RI, is .Saaty's randomized index 1977depends on the size of the developed matrix, as shown in the Table 6:

Table 6 randomized index

Size of matrix	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

After performing the calculations we found (12):

$$CR = \frac{\frac{\lambda_{max} - n}{n-1}}{RI} = \frac{\frac{4,276-4}{3}}{0,9} = 0.0924 \quad (12)$$

By this result in *CR* we can conclude the consistency of the judgements in our comparison matrix with a consistency ratio below 0.1.

Evaluation

Here comes the final step in our approach to reclassify the suppliers by getting the finding of the suppliers score calculation, table 7 presents the data for each supplier criteria contributing to this study explained previsiouly

The calculation of the scores for the different suppliers and their multi-criteria classification summarized in Table 8 after normalization. So, the results analysis lead us to prioritize and reclassify suppliers table 9, the best supplier keeping working with is F4 with a score of 0.70 in dark green, followed by F3 with a score of 0.67 and in third place F7 with a performance of 0.65 according to all evaluation criteria above. Furthermore, we can conclude to the range of supplier performance affecting quality of products delivered which is very significant, with a maximum score of 0.70 and a minimum score of 0.37.

Using this AHP approach, which calculates a score for each supplier, the company can select and know, in order of priority, the automotive textile suppliers who must remedy their situation requesting an improvement action, starting with those classified in yellow and then those classified in blue, as shown in Table 8 above.

Table 7 Supplier data table

Supplier	customer service and technical support	Quality of product or service	production capacity and stock availability	Innovation and R&D
F 1	5	10	5000	1
F 2	6	6	7500	3
F 3	3	3	10000	4
F 4	2	5	5500	2
F 5	7	7	10500	2
F 6	4	5	12000	5
F 7	4	4	6500	3
F 8	7	8	8800	2
F 9	9	9	9500	3
F 10	5	12	7000	2
F 11	3	6	20000	6
F 12	4	4	16000	5
F 13	9	11	6000	3
F 14	8	8	10500	4
F 15	3	4	12500	5

Table 8 Supplier evaluation table

	customer service and technical support	Quality of product or service	production capacity and stock availability	Innovation and R&D	
Weight	0.06982659	0.43455379	0.29928778	0.19633184	Final calcul
F 1	0.4	0.3	1	1	0.65391639
F 2	0.33333333	0.5	0.66666667	0.33333333	0.50552156
F 3	0.66666667	1	0.5	0.25	0.6798317
F 4	1	0.6	0.90909091	0.5	0.70080458
F 5	0.28571429	0.42857143	0.47619048	0.5	0.4468717
F 6	0.5	0.6	0.41666667	0.2	0.45961518
F 7	0.5	0.75	0.76923077	0.33333333	0.65649395
F 8	0.28571429	0.375	0.56818182	0.5	0.45112392
F 9	0.22222222	0.33333333	0.52631579	0.33333333	0.38333211
F 10	0.4	0.25	0.71428571	0.5	0.44851199
F 11	0.66666667	0.5	0.25	0.16666667	0.37137187
F 12	0.5	0.75	0.3125	0.2	0.49362244
F 13	0.22222222	0.27272727	0.83333333	0.33333333	0.44888212
F 14	0.25	0.375	0.47619048	0.25	0.37201527
F 15	0.66666667	0.75	0.4	0.2	0.53144788

Table 9 Supplier reclassification

Ranking	1	2	3	4	5	6	7	8	9	10
Suppliers	F 4	F 3	F 7	F 1	F 15	F 2	F 12	F 6	F 8	F 13
Score	0.70081	0.67983	0.65649	0.65392	0.53145	0.50552	0.49362	0.45962	0.45112	0.44888
Ranking	11	12	13	14	15					
Suppliers	F 10	F 5	F 9	F 14	F 11					
Score	0.44851	0.44687	0.38333	0.37202	0.37137					

4.2.4 Discussion

Recovery plan

It was crucial to consult with the purchasing manager, the director, and the quality team before determining the appropriate corrective actions for the suppliers identified in yellow in Table 9. This collaborative decision-making process ensures that any actions taken are in line with the company's strategic objectives and operational requirements.

To address the situation effectively, second-level escalation letters were issued to each supplier under the jurisdiction of this multinational automotive division. These letters served as formal requests for corrective action plans from suppliers who were not meeting the expected standards. The company required these suppliers to submit their plans and to commit to a 100% delivery compliance check over a period of three months, in accordance with the group's quality standards. This proactive monitoring aimed to ensure that the suppliers could meet the high-performance thresholds necessary to support the company's operations.

Should the suppliers fail to meet the agreed standards or fail to take appropriate corrective action within the specified timeframe, they would be subject to first-level escalation within the group of the multinational. This higher level of escalation would involve more direct intervention from senior management and could potentially result in the severing of the supplier relationship if performance did not improve.

Additionally, the situation required immediate attention to ensure that suppliers who deviate from agreed terms are addressed promptly. Replacing non-compliant suppliers is crucial, as continued failure to meet the company's requirements not only impacts operational efficiency but also tarnishes the company's reputation and diminishes its competitive position in the marketplace. Non-compliance could ultimately affect the brand image and the company's customer loyalty.

It is essential that the company forms partnerships with suppliers who are aligned with the strategic objectives and vision of this multinational automotive leader. By ensuring that suppliers meet the company's standards, the company can maintain a strong competitive edge, retain customer loyalty, and enhance its market position in the long term.

ABC classification

As a benefit from this study, to implement an ABC classification of suppliers based on the Pareto principle:

Class A: Suppliers representing 80% of value, though only 20% of the total number. These are high-priority suppliers that require significant strategic focus to maximize benefits.

Class B: Suppliers with moderate impact, where continuous improvement programs can be implemented.

Class C: Low-impact suppliers who can be replaced more easily or used for non-critical supplies.

This classification would allow the company to concentrate its efforts on the most strategic partners, optimizing both costs and risks, while enhancing the resilience of the supply chain in facing future challenges.

In conclusion, effective supplier relationship management is vital for ensuring that suppliers who do not meet performance standards are given the opportunity to improve. However, it is equally important to take decisive action when necessary, replacing those suppliers who cannot meet the required expectations, to safeguard the company's operational integrity and market competitiveness.

5 Conclusion

In the automotive industry, building the smart supply chain of the future requires continuous analysis and rigorous follow-up with suppliers, even well beyond the initial selection stage. Given the ever-stricter quality requirements, it has become essential to regularly assess the supplier panel against key performance indicators (KPIs), with a particular emphasis on quality metrics.Selecting suppliers in the automotive industry is a complex and highly strategic process. Multiple criteria must be considered to ensure that the chosen suppliers effectively contribute to the overall performance of the supply chain. The study identifies eight critical criteria, which include: Product or service quality, cost prices and costs, Terms of delivery, Production capacity and stock availability, Customer service and technical support, Innovation and R&D, Financial stability and reputation and finally Sustainability and social responsibility. By incorporating these criteria into the supplier selection process, automotive companies can significantly enhance their operational efficiency, reduce supply chain risks, and strengthen their competitive position as they transition toward a smart, responsive supply chain.

The use of the Analytic Hierarchy Process (AHP) method has proven particularly beneficial for this multinational automotive company. AHP allows the company to prioritize and reclassify its supplier portfolio based on their impact on quality KPIs. Here's how it translates into actionable outcomes:

Prioritizing critical suppliers: Through AHP, the company can identify suppliers with the weakest quality performance, enabling targeted corrective actions or exploring alternative partnerships.

Optimizing resource allocation: By focusing on high-performing suppliers, the company can allocate resources more efficiently and strengthen relationships with strategic partners.

Continuous improvement of customer-supplier relationships is crucial for maintaining an agile and effective supply chain. Leveraging the insights gained from AHP-based evaluations, the company can implement differentiated pricing strategies tailored to the performance of each supplier: incentives for high-performing suppliers: Offering more favorable payment terms or long-term contracts to suppliers who excel in quality metrics,
adjusting pricing negotiations for suppliers needing improvement, based on their impact on the company's strategy vision.

By optimizing these relationships, the automotive industry can adapt more quickly to market fluctuations, ensuring that its suppliers align with evolving strategic priorities. This approach enables the company to deliver added value to customers in terms of quality, reliability, and innovation. The findings from this research pave the way for continuous improvements to develop a more intelligent and responsive supply chain.

Our research has certain limitation, such as limitations of the AHP Method, this approach relies on subjective judgment, which may introduce bias into the decision-making process. Moreover, in this article we take the case of automotive industries that can make the difference, if we choose another sector, it must be a necessity to change the selection criteria to meet the requirements and characteristics of each sector. Building on the findings and limitations of this study, several potential avenues for future research could help deepen our understanding of supplier selection and performance evaluation in the automotive industry and beyond; Industry 4.0 technologies like IoT, AI, and big data analytics are being adopted by the automotive industry for effective supply chain management. The role of these tools in improving the evaluation phase where suppliers are evaluated based on their performance and risk forecasting could also be identified by future research. this research examines of machine learning methods would reduce subjectivity and provide a more data-driven approach to supplier selection., Further research could also have a specific issue such us a subject to treat impact of collaborative risk-sharing mechanisms on supplier performance and how these can contribute to a smart supply chain of tomorrow.

By leveraging methodologies such as AHP and ABC analysis, this integrated approach enables automotive companies to successfully navigate towards a smart, future-proof supply chain. Ensuring that every supplier aligns with objectives related to quality, cost, flexibility, and sustainability allows companies to not only meet current market demands, but also to anticipate future industry trends.

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Efficiency assessment of the Mongolian railway industry using data envelopment analysis: a comparative analysis with CAREC railways

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Keywords: efficiency, Mongolia, railway transportation industry, Central Asia Regional Cooperation (CAREC), Data Envelopment Analysis (DEA).
Abstract:
This study aimed to assess the efficiency of the railway industry in Central Asia Regional Economic Cooperation (CAREC) 10 member countries. Using data from 2016 to 2018, we set the ten CAREC countries as DMUs and applied the DEA (Data Envelopment Analysis) method to analyze the relative efficiency of each country's railway industry. Input factors considered were railway extension length, number of workers, freight cars, and expenses. Output factors included revenue and total cargo volume. The results revealed that the China Railway Corporation and the Afghanistan Railway Authority consistently demonstrated efficiency over three years, with an efficiency value of 1(100%). Kazakhstan and Uzbekistan also achieved 100% efficiency for one year each. While the Mongolian railway industry showed a slightly higher efficiency index, it was less efficient than China, Afghanistan, Kazakhstan, and Uzbekistan. Findings reveal that the Mongolian railway sector faces significant challenges due to outdated infrastructure, rolling stock, and equipment, which hinders profitability. According to the results of DEA's analysis, it is helpful for Mongolia to choose optimal benchmarking targets to reduce operating costs, improve infrastructure and facilities, and optimize operations to enhance railway efficiency.

1 Introduction

Mongolia spans an area of 1,564,116 square kilometers in Central Asia. This landlocked nation shares its northern border with Russia and its southern border with China. Despite limited international trade and logistic networks via its neighbors, Mongolia is traversed by a continental railway line that connects Eurasia. The history of Mongolia's railway industry dates back to 1938, with an initial railway line stretching 43 kilometers and featuring a 750 mm gauge. This line facilitated train travel between Ulaanbaatar and Nalaikh. In 1946, the Mongolian and Russian governments negotiated a contract establishing the Mongolian Railway joint venture. By 1955, the ownership was split evenly at 50:50. The Russian government completed a 400 km railway line connecting Ulaanbaatar to Naushki in 1949, and a 700 km line linking Ulaanbaatar to Zamiin-Uud was finished in 1955. In 1952, an agreement was reached among Russia, China, and Mongolia to operate interconnecting direct trains through Mongolia, leading to the opening of the Trans-Mongolian Railway (TMGR) in 1956.

As of 2023, Mongolia's railway network extends to 2,413 km, primarily comprising two main and eight branch lines. A 1,110 km route connects Sükhbaatar on the Russian border, passing through the capital Ulaanbaatar to Zamiin-Uud on the Chinese border. As a landlocked country, Mongolia's nearest port to the capital, Ulaanbaatar, is Tianjin Port in China, approximately 1,700 km away. The Mongolian railway shares the same broad gauge (1520 mm) as Russia, but when trading with China, which uses the standard gauge (1435 mm), transshipment is necessary due to the gauge difference. This gauge difference significantly impacts logistic flow and the time and cost of Mongolia's trade with China.

Mongolia's transportation sector encompasses railways, roads, and aviation. According to the Ministry of Road and Transport of Mongolia, the freight volume continues to rise annually, with an average annual cargo volume of 174 million tons as of 2023, reflecting a 76.6% increase from the previous year. The distribution of cargo transport among the different sectors is as follows: road transport accounts for 66.36%, railways for 33.63%, and air transport for 0.01%. In 2023, most of the international cargo (96.3%) was transported through the border with China, while the remainder (3.7%) passed through the border with Russia. Of the cargo handled at the Chinese border, 95.4% was exported transportation, whereas 88.9% was imported transportation at the Russian border.

Despite significant efforts, Mongolia's transportation efficiency needs to catch up to that of advanced countries. The aging railway infrastructure and a shortage of freight cars and locomotives necessitate extensive repairs and upgrades to enhance operational efficiency [1]. Furthermore, most railway routes are single-track, leading to increased freight transportation time due to delays at intermediate stations as train frequency rises. This inefficiency hinders the ability to meet the growing demand for freight transport. To address these challenges, the Mongolian government has devised a multi-stage plan to construct new railways, aiming to improve the overall transportation infrastructure and boost the competitiveness and efficiency of railway transportation. Additionally, several international organizations are investing in and implementing projects within the railway sector to support these improvements.

The CAREC Program is one of ADB's initiatives to foster regional cooperation and trade. It was launched in 2001 and is a partnership of 11 member countries. This study analyzes Mongolia's railway industry's efficiency by comparing it with the efficiency of the other ten Central Asia Regional Cooperation (CAREC) countries using open data from 2016 to 2018 from the Asian Development Bank (ADB)—Mongolia, which joined CAREC in 2003.

The efficiency research maximizes the benefits of investment and improvements in the railway industry; by measuring efficiency, the study seeks to identify inefficiencies in input factors and propose strategies for improvement, enabling the industry to achieve higher efficiency through benchmarking. In the case of rail transportation, the process for obtaining output is very complex, and according to [2-4], there are limitations in clearly identifying the input elements and costs. Considering the characteristics of the industry, we decided to apply the Data Envelopment Analysis (DEA) model, a linear programming method (LP).

This study comprises the following chapters: Chapter 1 introduces the study, Chapter 2 introduces related literature studies, and Chapter 3 briefly explains the methodology, specifically the DEA. Chapter 4 discusses efficiency, summarizes the analysis and results, presents opinions on Mongolia's efficiency, problems, and directions for improvement, and provides a simple interpretation of each country's efficiency. It concludes in Chapter 5.

2 Literature review

Much of the existing research on the railway sector was conducted on operational efficiency using various methodologies targeting routes and operating organizations. The efficiency of the railway systems in 19 Organization for Economic Cooperation and Development (OECD) countries was studied from 1978 to 1989 using DEA analysis. Tobit regression was used to ascertain the impact of public subsidies and the level of management autonomy while controlling for various operating characteristics and market environments, such as traffic density, average load per train, average travel distance, and electrification ratio. The study determined that railway systems heavily reliant on public subsidies exhibited significantly lower efficiency than those with lower dependency, and systemized countries tended to achieve higher efficiency levels [2].

This paper evaluates the performance of rail transport services by examining the comprehensive concept of service delivery from the perspective of railroads. Considering the limitations imposed by data availability and employing Data Envelopment Analysis (DEA), we have selected specific quality of service metrics. These metrics include punctuality, the frequency of severe train accidents (safety), and the volume of public complaints (customer satisfaction). The study identifies exemplary zones and assesses the efficiency of 16 Indian Railways (IR) zones based on these criteria [3]. In a study by [4], the causes and magnitudes of inefficiencies in the input structure were analyzed by applying DEA (DEA-AR) to evaluate the efficiency of the Chinese railway industry. The analysis results spanning 1985 to 2004 indicated an overall inefficiency within the Chinese railway industry, with a notable increase in efficiency observed after 2000. The study identified excessive workforce and outdated facilities as primary factors contributing to inefficiency. [1] analyzed the efficiency of railway transportation in Korea using DEA techniques based on railway transportation service data provided by 22 national railway operating companies from 2000 to 2006. The analysis showed that Korea's railway transportation operates more efficiently than other countries and that productivity has increased since 2004. [5] analyzed productivity changes in European railways from 1970 to 1995. The paper applied a non-parametric approach that could subdivide production changes into efficiency and technological changes. The results of the analysis confirmed that most companies focused on increasing productivity from 1985 to 1995 when they carried out the renovation process. Researchers of [6] analyzed the determinants of efficiency and found that, unlike other papers, the higher the autonomy and financial independence, the higher the efficiency level and technological change. [7] assesses the efficiency of 18 railway lines operated by seven major companies in Tokyo, factoring in financial performance and in-vehicle congestion. Using 2017 data on congestion rates, line specifics, passenger metrics, revenue, and expenses, the study applies data envelopment analysis and Tobit regression. Results show that adding congestion data improves service quality measurement in efficiency scores. Higher congestion lowers cost efficiency but boosts revenue efficiency, with improvement strategies proposed for different line types. [8], investigated the impact of CO2 emissions on railway efficiency in China, utilizing a Malmquist–Network DEA model with data from 18 railway bureaus from 2006 to 2020. Also, [9] examined railway transport in 16 nations between 2010 and 2018 using a three-stage DEA modeling approach. The 16 nations under consideration have comparable pure efficiencies but differing scale efficiencies, suggesting little chance of increasing efficiency through technical advancement.

In this study, we analyze the railway operation efficiency of CAREC countries, including Mongolia, based on DEA, find countries corresponding to the efficient frontier based on DEA, and benchmark the efficiency of the efficient frontier to suggest directions for improving Mongolia's efficiency. The summary of the literature review is shown in (Table 1).

Table 1 Summary of the relevant literature on Railway

Author	Subject	Input / Output	Methodology
Cantos, P., Pastor, J.M., and Serrano, L. (1999)	European Railway (1970~1995)	Number of workers, consumption of energy and materials, number of passenger carriages, number of freight cars, number of kilometers of track	DEA, MPI
		Passenger-km and tonnes-km	
Ha, H., C, Y., and Na, J. (2009)	China's Railway Industry (1985~2004)	Labor, power, capital, fuel consumption, GDP, railway length	DEA-AR
		Passenger-km, freight ton-km	
Kim, H., Kwang H., et al., (2009)	OECD 30 countries and Korean railways (2000~2006)	Workforce, fuel, vehicle, mainline extension, management cost	DEA, MPI
		Distance of traffic, train transport performance, transportation income data	
Sharma,M.G., Debnath,R.M., et al., (2016)	Indian Railway Passenger Transportation (2004~2009)	Working expense, financial performance, asset utilization, Number of employees, Equated Track kilometers	DEA, MPI,
		Loading of revenue-earning goods traffic, passenger traffic, punctuality of mail/express and suburban trains, mean kilometers per accident, number of satisfied passengers per complaint, reliability	
Kutlar, A., Kabasakal, A., and Torun, P. (2013)	World Railway firms (2000~2009)	Annual cost of operation, the average annual number of employees, the length of the main line, the number of traction vehicles, the number of passenger cars, the number of cargo cars	Panel data, DEA CCR – BCC, MPI
		Annual total revenues earned, total number of passengers transported, total number of passengers - km, total cargo ton transported, total cargo ton-km	
Oum, T., Yu C. (2014)	OECD 19 countries (1978~1989)	Labor, energy consumption, ways and structures, materials, number of passenger cars, number of freight wagons, number of locomotives	DEA, Tobit Regression
		passenger-km and freight ton-km, passenger train-km and freight train km	
Le, Y., Oka, M., & Kato, H. (2022)	Urban Railway (2008~2018)	Length of line, the number of stations, labor costs, operating costs, Vehicle kilometers, number of passengers	DEA, Tobit Regression
		Vehicle kilometers, number of passengers, 1/in vehicle congestion rate, fare revenue, miscellaneous transportation revenue	
Niu, Y., Li, X., et al., (2023)	16 Countries Railway (2010~2018)	Length of railway lines, average number of staff, number of locomotives, annual consumption of energy by railway transport, ratio of non-electrified railway tracks to electrified railway tracks	DEA
		Passenger-kilometers, freight-tonnes-kilometers	
Ji, W., & Qin, F. (2024)	China Railway bureaus (2006~2020)	Construction capital, line length, number of locomotives, number of employees, energy consumption of locomotives, population density, passenger delivery, per capital GDP, kilometers travelled by locomotives	Malmquist–NDEA model
		Revenue of railway transport, CO_2 emissions	

3 Methodology

Many researchers introduced efficiency analysis to the economics literature, and since then, many studies have been devoted to measuring efficiency. In particular, the fields of efficiency analysis are increasingly dominated by parametric frontier models and nonparametric techniques. Technical Efficiency (TE) and (Allocative Efficiency) AE use parametric and nonparametric methods in studies where economic efficiency performance assessment is measured. The nonparametric approach uses linear programming to determine the best combination of inputs and outputs, which are then categorized according to their actual performance to assess the relative effectiveness of many decision-making units.

The nonparametric approach has the advantage of imposing no a priori parametric restrictions on the underlying technology. DEA is an effective non-parametric method for evaluating the relative efficiency of the decision-making units, which can be different from the exact functional form between the inputs and outputs approach. The model measures the efficiency of all DMUs without requiring prior weights for the inputs and outputs. As a result, DEA computations are made to optimize each unit's relative efficiency score, with the caveat that the weights determined in this way for each DMU must also be practical for every other DMU in the sample. The DEA technique allows each DMU to set its variable weight more favorably than other DMUs and can identify reference units for each DMU. The DEA is more flexible and applicable than other methods [10].

In this study, the Data Envelopment Analysis (DEA) method is used to measure the overall efficiency of the railway systems.

3.1 Data Envelopment Analysis

Efficiency is defined as the ratio between outputs and inputs, and we can describe it as the distance between the quantity of input and output. Efficiency refers to the extent to which output can be produced with minimal input or the extent to which maximum output can be achieved with a given amount of input. Efficiency is measured by evaluating performance by comparing two or more production systems. It is a significant tool for analysis and improvement. It can be expressed as shown in equation (1).

$$Efficiency = \frac{OUTPUT}{INPUT} \quad (1)$$

The DEA model is an efficiency measurement method first developed based on the concept of relative efficiency by Farrell (1957), the CCR model by Charnes, Cooper, and Rhodes (1978) [11] developed the Farrell view, and they provided a fractional and nonlinear mathematical programming model to measure efficiency with multiple inputs and outputs. The BCC model by Banker, Charnes, and Cooper (1984) presented a new little changed model [12]. This method measures efficiency by calculating the production frontier, the minimum input combination required to produce a given output, the cost curve, and the distance between actual observation points. DEA models also require input- and output-oriented solutions to achieve an efficient frontier.

The input-oriented model offers recommendations for lowering inputs to reach the efficient frontier. The output-oriented model suggests ways to boost output to achieve an efficient frontier. The efficient frontier may be reached in the output-oriented model by increasing outputs without drawing in more inputs. The output-oriented paradigm makes sense when the inputs are roughly constant. Furthermore, the input-oriented paradigm works well when the outputs closely match the organization's objectives or are constrained by outside variables [13].

The DEA model is the most efficient method for evaluating input and output by applying each analysis target, or Decision-Making Unit (DMU), to both input and output. This model has the advantage of measuring the relative efficiency of DMUs with multiple inputs and outputs, enabling the assessment of both efficiency and inefficiency. These measurement results help analyze the causes of inefficiency and set goals for efficiency improvement. The DEA model is widely used for evaluating the efficiency of public service organizations [1]. In general, the CCR model is a fundamental model of the DEA technique, which can be explained as follows: The ratio of the weighted sum of output variables to the weighted sum of input variables in a DMU must not exceed 1, with the constraint that the weight of each input variable is greater than 0. The relative efficiency is evaluated based on this constraint. The DMU is considered inefficient if the calculated efficiency score is less than one.

The CCR model assumes that there are n DMU_j $(j = 1,2 \ldots . s)$ that produce s outputs for $y_{rj}(r = 1,2 \ldots . m)$, using inputs $x_{ij}(i = 1,2 \ldots . n)$, to be evaluated. The efficiency of a specific decision-making unit DMU_o is the ratio of the weighted sum of outputs divided by the weighted sum of inputs. In mathematical forms, it is shown in equation (2).

$$Max\ E_o = \frac{\sum_{r=1}^{m} u_r \ y_{r0}}{\sum_{i=1}^{n} v_i \ x_{io}}$$

$$s.t. \quad \frac{\sum_{r=1}^{m} u_r \ y_{rj}}{\sum_{i=1}^{n} v_i \ x_{ij}} \leq 1 \quad j = 1,2, \ldots, s$$

$$and\ u_r, v_i > 0, \ (r = 1,2, \ldots, m)\ (i = 1,2, \ldots, n) \quad (2)$$

Where the x_{ij}, y_{rj} are the known inputs and outputs of the j^{th} DMU. The models presented in above ratio form are a fractional programming problem. Nevertheless, since $\sum_{i=1}^{n} v_i \ x_{ij} \geq 0$, if we let $\sum_{i=1}^{n} v_i \ x_{i0} = 1$, the problem can be reformulated as the following linear programming problem as shown in equation (3).

$$Max\ E_o = \sum_{r=1}^{m} u_r\ y_{r0}$$
$$s.t.\quad \sum_{i=1}^{n} v_i\ x_{i0} = 1,$$
$$\sum_{r=1}^{m} u_r\ y_{rj}\ \leq \sum_{i=1}^{n} v_i\ x_{ij},\quad j = 1,2 \ldots, s$$
$$and\ u_r, v_i > 0, (r = 1,2, \ldots, m)\ (i = 1,2, \ldots, \mathrm{n}) \quad (3)$$

Where:
$DMUo$: $Decision\ Making\ Unit$,
$\boldsymbol{E_o}$: $\boldsymbol{Efficiency\ of\ DMUo}$,
$\boldsymbol{u_r}$: $\boldsymbol{weight\ for\ r^{\ th} output}$,
$\boldsymbol{v_i}$: $\boldsymbol{weight\ for\ i^{th}\ input}$,
$\boldsymbol{y_{rj}}$: $\boldsymbol{the\ amount\ of\ r^{\ th}\ output\ of\ DMUj}$,
$\boldsymbol{x_{ij}}$: $\boldsymbol{the\ amount\ \ of\ i^{th}\ input\ of\ DMUj}$,
$\boldsymbol{r}$: $\boldsymbol{number\ of\ outputs}$,
$\boldsymbol{i}$: $\boldsymbol{number\ of\ inputs}$,
s: number of DMUs to evaluate.

Hence, solutions can be derived through the iterative use of linear programming software.

The CCR model assumes constant returns to scale (CRS) in the productivity process and measures efficiency and overall technical efficiency (TE) [11].

3.2 CCR model for DMU-1(Mongolia)

Rail transportation is a public sector, so measuring the cost of input and output factors, the importance of services provided, and the resources used to depend on the evaluation target is difficult. Therefore, considering these characteristics, data envelopment analysis (DEA) models are widely used for evaluation, and this study uses an input-oriented model.

Regarding Mongolia's railways, it has been many years since the primary railway network was established, and it is challenging to completely repair and modernize it, mainly since all export, import, and transit cargoes are transported along a single main route. In this input-oriented model, one of the main objectives is to maintain the output level while enhancing the input level. Although it is difficult to carry out large-scale works such as expanding railway tracks in a short period, we selected this model because it is possible to improve the input factors such as the number of vehicles, personnel, and operating costs that can be enhanced to control the railway organization.

Mongolia's primary railway network has an average carrying capacity of 25 tons per axle (Axle Load). However, the load has increased in recent years, leading to overloading on some routes. This overloading has damaged the railway infrastructure, increased maintenance costs, affected the quality of the railway, and raised the probability of accidents, all of which directly impact performance. In the future, the volume of transportation and profitability will depend on the railway's capacity; therefore, there is a need to enhance the quality of the existing inputs to increase output. We have chosen this method because it is the most efficient way to carry out rail transport until the dual tracks and new transport corridors are created as part of the railway reform.

Accordingly, a basic model with a specific direction that can fix the output and reduce the input and a radial model that can obtain the same efficiency score regardless of unit change in input and output were assumed. The input-oriented envelope model is "a model that finds the $\boldsymbol{\theta}$ ratio that reduces the input level to the smallest by reducing all m input factors by a certain percentage while achieving at least the same output level as the current output level. " Let's calculate and interpret the efficiency of the railroad industry using the objective function and constraint formula of the linear planning method of the input-oriented envelope model. Assume there are 10 DMUs, and each DMU $(\boldsymbol{j = 1, 2, \ldots, 10})$ produces $\boldsymbol{y_{rj}(r = 1, 2, \ldots, m)}$ output variables by inputting $\boldsymbol{x_{ij}(i = 1, 2, \ldots, n)}$ input variables. First, if the weight of input elements 1 to 4 are $\boldsymbol{v_1, v_2, v_3, v_4}$, and the weight of output elements 1 and 2 are $\boldsymbol{u_1, u_2}$, the CCR input-oriented model for calculating the DEA efficiency score of $\boldsymbol{DMUE_1}$ can be formulated as following equation (4).

$$\begin{aligned}
&\boldsymbol{Max\ E_1 = 19,989u_1 + 128,975u_2}\\
&\boldsymbol{s.t.\ \ 13364v_1 + 1810v_2 + 3319v_3 + 129,329v_4 = 1}\\
&\quad \boldsymbol{19,989u_1 + 128,975u_2 \leq 13364v_1 + 1810v_2 + 3319v_3 + 129,329v_4}\\
&\quad \boldsymbol{5,190u_1 + 213,284u_2 \leq 22886v_1 + 2066v_2 + 4193v_3 + 217,629v_4}\\
&\quad \boldsymbol{2,693,000u_1 + 89,259,332u_2 \leq 2,003,306v_1 + 111821v_2 + 764783v_3 + 82,236,988v_4}\\
&\quad \boldsymbol{339,000u_1 + 1,708,912u_2 \leq 76240v_1 + 15529v_2 + 56504v_3 + 1,367,884v_4}\\
&\quad \boldsymbol{10,000u_1 + 200,412u_2 \leq 12700v_1 + 1994v_2 + 4469v_3 + 135,202v_4}\\
&\quad \boldsymbol{1,742u_1 + 18,391u_2 \leq 326v_1 + 75v_2 + 17v_3 + 10,444v_4}\\
&\quad \boldsymbol{12,421u_1 + 71,936u_2 \leq 80054v_1 + 7791v_2 + 15164v_3 + 144,001v_4}\\
&\quad \boldsymbol{5,454u_1 + 51,8876u_2 \leq 5770v_1 + 597v_2 + 450v_3 + 49,358v_4}\\
&\quad \boldsymbol{67,600u_1 + 63,5326u_2 \leq 58239v_1 + 4593v_2 + 20448v_3 + 56,015v_4}\\
&\quad \boldsymbol{6,031u_1 + 56,903u_2 \leq 5131v_1 + 417v_2 + 1080v_3 + 38,603v_4}
\end{aligned} \quad (4)$$

$$and\ u_1, u_2, v_1, v_2, v_3, v_4 \geq 0$$

To obtain the optimal solution of the above linear programming model using MS Excel Solver, the Mongolian railway industry, which is the subject of evaluation, uses input and output variables such as 13,364 staff (v_1), 1,810 km of railway line extension (v_2), 3,319 freight vehicles (v_3), and operating expenses of USD 12.9 billion (v_4), resulting in railway freight performance of 19,989 tons of freight (u_1) and USD 12.8 billion in revenue (u_2) to obtain the DEA efficiency score.

3.3 Data collection

Since there is no precise definition of input and output factors, it is essential to define which factors are used as inputs and outputs together with the evaluation criteria. Considering the characteristics of railway transport and the availability of reliable information, input and output factors must be finalized, so factors relevant to the railway industry were selected from previous research. The data used in this study is based on the 2016-2018 Railway Sector Report of Member States published by the ADB. Also, the homepages, statistical websites, and press releases of the country's railway organizations were analyzed, and missing and additional information not included in the report was found. The data set consists of 10 countries in CAREC that do not have Turkmenistan. Because it does not provide data as simultaneously as other countries. The inputs and outputs used in this paper focus on the ten CAREC countries and review previous studies on railway efficiency using the DEA method. The available data from the cost-effectiveness analysis (Table 2) are summarized.

Table 2 Numerical value of input and output data (2016~2018)

DMU	Nation	Year	Employee	Rail length (km)	Freight car	Expenses (million)	Freight volume (million)	Revenue (million)
1	Mongolia	2016	13,364	1,810	3,319	129,329,438	19,989,000	128,975,110
		2017	15,800	1,815	6,500	131,396,347	22,765,000	156,494,526
		2018	16,482	1,920	7,130	135,234,892	25,763,000	181,887,977
2	Azerbaijan	2016	22,886	2,066	4,193	217,629,533	5,190,000	213,284,345
		2017	19,000	2,944	4,193	251,214,852	4,630,000	225,982,681
		2018	19,000	4,285	4,193	287,268,868	4,490,000	222,192,685
3	China	2016	2,003,306	111,821	764,783	82,236,988,290	2,693,000,000	89,259,332,909
		2017	1,848,032	131,000	808,736	88,298,554,192	3,689,000,000	97,145,983,456
		2018	1,841,500	132,000	839,213	94,318,371,635	4,026,000,000	104,425,165,720
4	Kazakhstan	2016	76,240	15,529	56,504	1,367,884,179	339,000,000	1,708,912,128
		2017	119,071	16,040	54,925	1,497,596,421	387,000,000	1,895,768,595
		2018	130,400	16,040	55,000	1,699,228,918	387,000,000	2,167,872,187
5	Georgia	2016	12,700	1,994	4,469	135,202,727	10,000,000	200,412,171
		2017	10,765	1,443	5,001	284,672,249	10,600,000	175,951,569
		2018	13,000	1,443	5,001	404,665,087	9,900,000	165,032,421
6	Afghanistan	2016	326	75	17	10,444,413	1,742,000	18,391,248
		2017	326	75	17	11,366,813	1,968,000	19,540,701
		2018	326	75	17	10,458,603	3,298,000	29,871,588
7	Pakistan	2016	80,054	7,791	15,164	144,001,414	12,421,000	71,936,068
		2017	72,078	7,791	16,085	143,283,202	20,884,000	71,939,659
		2018	72,078	7,791	16,159	153,542,854	20,849,000	89,004,365
8	Tajikstan	2016	5,770	597	450	49,358,470	5,454,000	51,887,272
		2017	5,700	680	450	30,813,922	4,647,000	33,623,702
		2018	5,400	682	450	33,998,339	5,348,000	37,744,712
9	Uzbekistan	2016	58,239	4,593	20,448	56,015,791	67,600,000	63,532,616
		2017	64,100	4,669	20,448	36,831,650	67,900,000	76,728,643
		2018	70,000	4,718	20,448	81,615,768	68,400,000	83,461,310
10	Kyrgyz	2016	5,131	417	1,080	38,603,219	6,031,000	56,903,831
		2017	4,700	424	1,080	54,984,268	7,157,000	61,720,401
		2018	4,817	424	1,080	48,365,901	7,526,000	56,020,596

*Data was collected from the report of Railway Sector Assessment CAREC countries, ADB (2022) [14].

4 Results and discussion

This study conducted a DEA efficiency analysis on ten national railway industries from 2016 to 2018, spanning three years. Turkmenistan was excluded from the analysis due to insufficient information on its profits and operating costs among the 11 national railway institutions of CAREC member countries. MS Excel Solver was used as the analysis tool. The DEA model evaluates a DMU with an efficiency value of 1 as the most efficient; if the value is less than 1, the DMU is considered relatively inefficient. The trend of efficiency changes for each national railway operating industry is shown in (Figure 1).

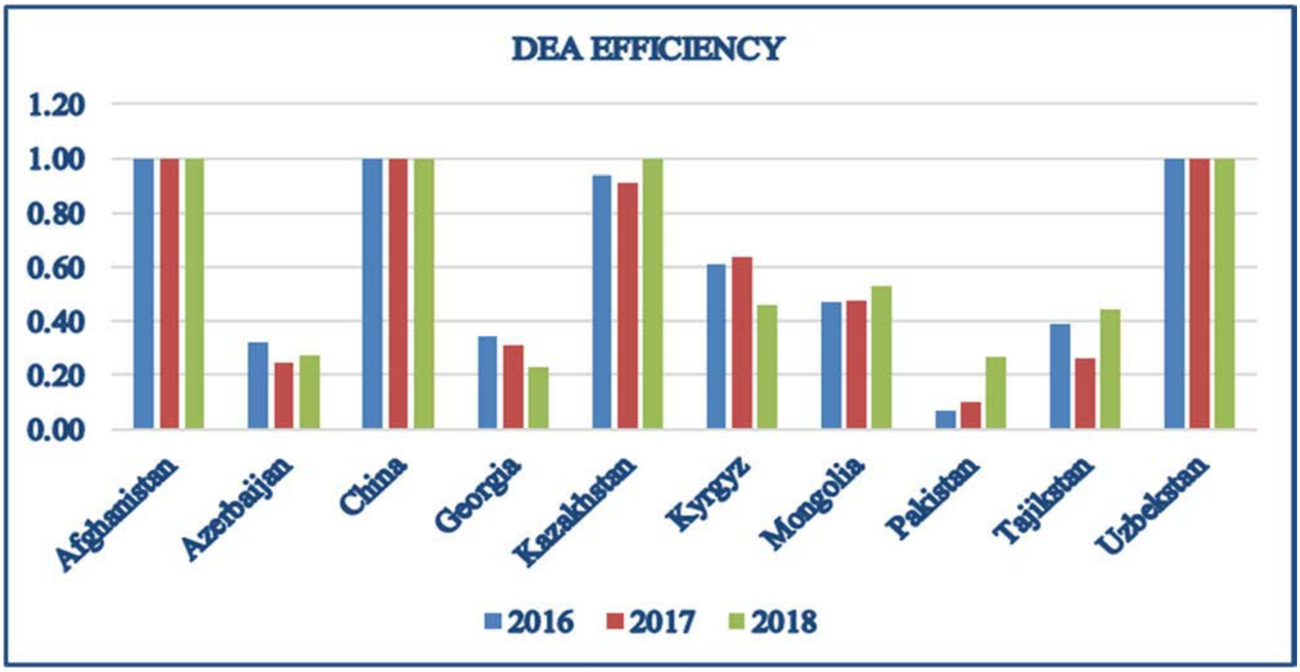

Figure 1 Efficiency of the 10 DMUs

The analysis results using the CCR model are shown in (Table 3). When measuring the operational performance of the countries operating the railways, the total performance of the operating income and the total amount of transported freight were selected to measure the efficiency. As a result, four of the railway organizations were efficient, and six were analyzed as inefficient. The institutions operating at 100% efficiency are China Railway Corporation (DMU-3), Afghanistan Railway Authority (DMU-6), Kazakhstan Railways (DMU-4), and Uzbekistan Railways (DMU-9) have worked efficiently for one year each. Afghanistan Railway Authority (DMU-6) was the most efficient DMU analyzed 22 times for the DMU with the most significant reference group. After that, China Railway Corporation (DMU-3) had many references, 15, and finally, Uzbekistan Railways (DMU-9) was analyzed as the subject of efficiency evaluation four times.

It has been concluded that the Mongolian railway sector (DMU-1) did not operate at 100% efficiency during the specified years. The Mongolian railway fleet suffers from significant wear and tear, with approximately 60% of logistics elements, such as wagons and locomotives, being at least 26 years old. These vehicles operate under harsh conditions and often receive minimal maintenance, rendering them prone to increased deterioration. According to data from the International Union of Railways (UIC), UBTZ ranks third lowest in the number of wagons among comparator countries and fourth in the number of diesel locomotives (2017). However, from 2016 to 2018, the efficiency rate gradually improved, rising from 47.4% in 2016 to 47.5% in 2017, reaching 51% in 2018. This improvement can be attributed to a continuous increase in freight performance, operating income, and output factors. Specifically, cargo flow throughput increased from 19.989 million tons in 2016 to 25.763 million tons in 2018, reflecting an annual growth rate of approximately 13%. Simultaneously, operating profit rose by 26%, from 156.494 million to 181.887 million. Additionally, the growth rate of operating expenses remained low and was effectively managed. If activities such as the comprehensive renovation of the existing railway fleet, technical logistics, the acquisition of new equipment, and timely maintenance are undertaken, the productivity of railway operations could reach 100%. Furthermore, the Mongolian government has recently initiated a new railway project aimed at expanding the railway network and enhancing mining operations, which are critical factors influencing the development of the railway industry. As part of this project, the railway network will be expanded, leading to increased cargo volume and enhanced efficiency within the Mongolian railway sector.

Azerbaijan Railways (DMU-2) 's efficiency decreased year over year from 2016 to 2018, directly related to higher operating income than expenses. The main reason is that during this period, Azerbaijan Railways invested a lot of finance in the project, investing in the infrastructure works to connect the Baku-Tbilisi-Kars BTK railway line. Once the project is fully implemented, it will cover expenses, increase income, and be profitable. The Baku-Tbilisi-Kars (BTK) railway connects Baku, Azerbaijan, with Tbilisi, Georgia, and Kars, Turkey. The line is an important transit corridor from the Caspian Sea to Europe and has developed into one of the main routes connecting China, Central Asia, the Caucasus, and Europe. In 2016-2018, the efficiency of China's railways (DMU-3) improved due to the expansion of high-speed rail and the growth of passenger flow and freight revenue. During this period, China expanded its domestic and international rail network and increased shipments to Europe under the Belt and Road Initiative, contributing significantly to revenue. Profitability has also been boosted by introducing technologies to control costs, reduce excessive workforces, and improve operational efficiency. Although the liabilities of the railway sector have increased, long-term profitable investments have stabilized profitability. China's railway network remained generally financially stable and profitable during this period.

The efficiency of Kazakhstan's railways has steadily increased year after year, and research has confirmed that it was 100% efficient in 2018. During this period, the increase in freight revenue, especially in China-Europe transit traffic, was a key factor supporting profitability. The volume of transport flow is growing every year, and Kazakhstan has developed into one of the leading trade routes of Eurasia. Also, infrastructure improvements and technological innovations have reduced costs and increased efficiency. Kazakhstan Railways has expanded its international connections with countries such as Russia and China, further increasing its operating financial income. As a result, the country's railway industry has reached a financially stable and profitable state.

Table 3 Estimation result of railway industries efficiency

DMU	Nation	Year	V1	V2	V3	V4	U1	U2	Efficiency (%)	Reference point
1	Mongolia	2016	0.00E+00	2.37E-08	0.00E+00	5.50E-04	0.00E+00	2.79E-11	47.4	DMU 3, 6
		2017	0.00E+00	2.09E-08	0.00E+00	5.47E-04	0.00E+00	6.08E-11	47.5	DMU 3, 6
		2018	2.69E-09	5.92E-11	0.00E+00	0.00E+00	0.00E+00	7.71E-09	51.4	DMU 6, 9
2	Azerbaijan	2016	1.51E-09	0.00E+00	0.00E+00	3.63E-04	0.00E+00	1.15E-09	32.3	DMU 3, 6
		2017	1.09E-09	0.00E+00	0.00E+00	2.72E-04	0.00E+00	7.96E-10	24.6	DMU 3, 6
		2018	1.22E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.48E-09	27.1	DMU 6
3	China	2016	0.00E+00	2.09E-08	0.00E+00	5.47E-04	0.00E+00	8.50E-12	100.0	-
		2017	2.69E-09	5.92E-11	0.00E+00	0.00E+00	0.00E+00	7.52E-12	100.0	-
		2018	9.58E-12	0.00E+00	0.00E+00	2.90E-06	0.00E+00	6.54E-12	100.0	-
4	Kazakhstan	2016	0.00E+00	2.77E-09	1.75E-07	6.35E-05	0.00E+00	0.00E+00	93.8	DMU 3, 6
		2017	0.00E+00	2.36E-09	0.00E+00	6.17E-05	0.00E+00	6.87E-12	91.2	DMU 3, 6
		2018	9.58E-12	0.00E+00	5.68E-07	0.00E+00	0.00E+00	9.64E-12	100.0	-
5	Georgia	2016	1.72E-09	0.00E+00	0.00E+00	4.13E-04	0.00E+00	1.31E-09	34.5	DMU 3, 6
		2017	1.76E-09	0.00E+00	0.00E+00	4.39E-04	0.00E+00	1.29E-09	31.0	DMU 3, 6
		2018	1.40E-09	0.00E+00	0.00E+00	4.25E-04	0.00E+00	9.57E-10	23.1	DMU 3, 6
6	Afghanistan	2016	5.44E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.96E-06	100.0	-
		2017	5.12E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.70E-07	100.0	-
		2018	3.35E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.56E-08	100.0	-
7	Pakistan	2016	0.00E+00	5.52E-09	0.00E+00	1.28E-04	0.00E+00	6.49E-12	6.9	DMU 6
		2017	0.00E+00	4.89E-09	0.00E+00	1.28E-04	0.00E+00	1.43E-11	10.2	DMU 3, 6
		2018	0.00E+00	9.86E-09	0.00E+00	0.00E+00	3.29E-05	3.06E-09	26.7	DMU 6, 9
8	Tajikistan	2016	0.00E+00	7.19E-08	0.00E+00	1.67E-03	9.31E-06	0.00E+00	39.2	DMU 3, 6
		2017	0.00E+00	5.59E-08	0.00E+00	1.46E-03	0.00E+00	1.63E-10	26.0	DMU 3, 6
		2018	0.00E+00	8.31E-08	0.00E+00	0.00E+00	2.77E-04	2.57E-08	44.4	DMU 6, 9
9	Uzbekistan	2016	0.00E+00	1.48E-08	0.00E+00	0.00E+00	4.76E-05	4.89E-08	63.3	DMU 3, 6
		2017	0.00E+00	1.47E-08	0.00E+00	0.00E+00	4.85E-05	2.45E-08	57.6	DMU 6
		2018	0.00E+00	1.46E-08	0.00E+00	0.00E+00	4.87E-05	4.53E-09	100.0	-
10	Kyrgyz	2016	0.00E+00	1.03E-07	0.00E+00	2.39E-03	0.00E+00	1.21E-10	61.2	DMU 3, 6
		2017	0.00E+00	8.88E-08	0.00E+00	2.32E-03	0.00E+00	2.59E-10	63.5	DMU 3, 6
		2018	0.00E+00	6.11E-08	0.00E+00	8.84E-04	0.00E+00	1.29E-08	46.9	DMU 6, 9

Georgian Railways (DMU-5) operated at a loss because expenses exceeded income in 2016-2018. During this period, the organization made significant investments, such as the Baku-Tbilisi-Kars (BTK) railway project, which may have adversely affected profitability. Higher operating costs, maintenance, and employee costs that exceeded revenue were the main reasons for the loss. Also, transit demand volatility and transport revenue dependence have increased economic risks. In addition, the burden of loans and liabilities may also hurt income. Therefore, it can be assumed that short-term financial difficulties cause the loss of Georgian Railways. As a result, operating costs also increased sharply from 284 million to 404 million, and operating profit and freight transport performance did not increase that much, which is believed to have continuously decreased efficiency.

The main reasons for Afghanistan Railways' (DMU-6) showed an efficiency of 100% every year in its efficiency measurement value. Afghanistan's crucial strategic location connects Central and South Asia and the Middle East, creating favorable transportation and logistics conditions. Afghanistan's railway network is relatively short; as of 2018, its total length was about 75 km. At that time, the main route was the line connecting the ports of Khairaton and Uzbekistan. Although the length of the railway was limited, the use of freight cars and increased transit traffic to the Middle East and Central Asia significantly impacted growing revenues. Although the number of freight cars may be low, higher international freight demand has increased the volume of freight transiting Afghanistan, which has positively impacted the profitability of the country's railways.

Despite its economic importance, Pakistan's railway (DMU-7) faced several challenges in 2018. The railway network is 7,791 km long and suffers from aging infrastructure. Technological innovation and automated systems are essential to improve the delivery of freight and passenger services. Lack of finance and harmful deficits are stabilizing the development of the industry, and the lack of political protection from the outside is used to eliminate the negative impact of strategic decisions. Improving sub-operations, attracting international investment, and developing cooperation with other countries are essential. Therefore, there is potential to transform energy, develop strategies for developing Pakistan's railway sector, and significantly impact economic growth.

Table 4 Average Efficiency of DMUs (2016~2018)

DMU	Nation	Year	Dea Efficiency	Average Efficiency
1	Mongolia	2016	47.4%	48.8%
		2017	47.5%	
		2018	51.4%	
2	Azerbaijan	2016	32.3%	28.0%
		2017	24.6%	
		2018	27.1%	
3	China	2016	100%	100%
		2017	100%	
		2018	100%	
4	Kazakhstan	2016	93.8%	95.0%
		2017	91.2%	
		2018	100%	
5	Georgia	2016	34.5%	29.5%
		2017	31.0%	
		2018	23.1%	
6	Afghanistan	2016	100%	100%
		2017	100%	
		2018	100%	
7	Pakistan	2016	6.9%	14.6%
		2017	10.2%	
		2018	26.7%	
8	Tajikistan	2016	39.2%	36.5%
		2017	26.0%	
		2018	44.4%	
9	Uzbekistan	2016	63.3%	73.7%
		2017	57.7%	
		2018	100%	
10	Kyrgyz	2016	61.2%	56.9%
		2017	63.5%	
		2018	46.9%	

Due to several factors, the Tajikistan Railway (DMU-8) was moderately efficient in 2016-2018. The overall length of the railway network was relatively short, limiting domestic transport capacity. The unstable demand for transit cargo is believed to have led to the risk of lower income. Profitability was adversely affected by the high operational and maintenance costs of railways. These factors are believed to have contributed to Tajikistan Railways' moderate profitability and the fact that there was too much labor force compared to the length of the railway extension and cargo vehicles.

During this period, the cargo transportation capacity of the Uzbekistan Railway (DMU-9) increased due to significant investments in infrastructure improvement and the construction of new lines. In 2018, the increase in demand for transit transportation supported the growth of freight traffic to the Middle East and Central Asia. The tariff policy made transport prices more flexible and increased competitiveness. In 2018, the efficiency measure was measured as 1, showing 100% efficiency, because Uzbekistan expanded its high-speed rail network, strengthened connections between major cities, and also applied eco-friendly technologies such as replacing existing diesel locomotives with electric locomotives or introducing hybrid technologies to reduce the energy consumption of railway vehicles.

In 2016-2018, the efficiency of the Kyrgyz Railways (DMU-10) was moderate due to the limited capacity of domestic transportation and the lack of opportunities for transit freight. The length of the railway network and the relatively low level of infrastructure development negatively affected profitability. Although specific projects and investments have been made, economic difficulties and political instability have limited investment. Freight revenues were volatile, and competitiveness could have been better. The inflexibility of the tariff policy also contributed to lower profitability. Therefore, the Kyrgyz railway sector has not achieved sustainable growth and requires significant reforms and investments for further development.

The average efficiency is shown in (Table 4). The average efficiency of each national railway industry was 0.4878 for DMU-1, 0.2799 for DMU-2, 1 for DMU-3, 0.9500 for DMU-4, 0.2953 for DMU-5, 1 for DMU-6, 0.1457 for DMU-7, 0.3654 for DMU-8, 0.7367 for DMU-9, and 0.5691 for DMU-10.

Examining the efficiency trends of each operating institution reveals a general increase over time. This improvement reflects the continuous efforts made by these institutions to enhance efficiency. However, inefficiencies persist, primarily due to rising operating costs. To reduce these costs and further boost efficiency, it is crucial to introduce digital technologies, improve energy efficiency, optimize operation management, utilize eco-friendly technologies, and enhance infrastructure. By implementing these measures, the railroad industry can operate more competitively and sustainably, leading to increased profitability in the long run.

5 Conclusions

In the previous studies of the Mongolian railway industry, many studies were conducted on the current status of Mongolian railways and railway construction plans, and studies on efficiency were rare. This study was conducted to measure the Mongolian railway transportation industry's efficiency and derive improvement points. Using the DEA method, this study analyzed the efficiency of railway institutions in 10 CAREC countries from 2016 to 2018. As a result of the efficiency analysis, 4 DMUs were interpreted as the most efficient operating institutions and 6 DMUs were analyzed as inefficient operating institutions.

Between 2016 and 2018, the operating efficiency of the railway sectors within the Central Asian Economic Cooperation varied significantly. The average efficiency of each operating agency was analyzed to be higher overall in agencies that operate large-scale urban railways or railways with small input elements. For three years, the China Railway Corporation and Afghanistan Railway Authority were analyzed as the most efficient operating institutions.

Also, China, Kazakhstan, and Uzbekistan achieved efficiency through effective policies promoting transit cargo transportation, infrastructure development, and substantial investment. In contrast, while Afghanistan's railway network is limited in length, it generated profits through the effective use of freight wagons and increased transportation to the Middle East and Central Asia. Conversely, Tajikistan and Kyrgyzstan experienced moderate profitability, hampered by infrastructure constraints, political instability, and insufficient investment. Georgia's railway network, characterized by exceptionally high expenditures, contributed to its poor performance. Research in Pakistan and Mongolia indicated that the railway infrastructure, rolling stock, and equipment were only partially profitable due to their outdated condition.

Therefore, it is concluded that future measures to enhance the operations of the Central Asian Economic Cooperation railway countries should include expanding the railway network, building new lines, and strengthening cooperation among regional countries. Additionally, improving the transit transport and logistics systems will be essential. These measures have the potential to support the growth of the Central Asian railway industry by reducing operating costs while enhancing safety and service quality.

According to the DEA analysis results, Mongolia would benefit from selecting appropriate benchmarking targets to reduce operating costs and optimize operations to improve railway efficiency. Railway infrastructure expenses, train operating costs, and corporate overhead costs are the three primary categories of expenditures associated with railways. The capital and maintenance expenses for the track, engineering structures (such as bridges and tunnels), signaling, communications systems, power supply, and terminal facilities are all included in the railway infrastructure costs. The costs of fuel or power, rolling stock and locomotive depreciation or leasing, crews, terminal operations, rolling stock maintenance, and commercial expenses (such as freight booking) are all included in train operating costs. Findings reveal that the Mongolian railway sector faces significant challenges due to outdated infrastructure, rolling stock, and equipment, which hinders profitability. It is necessary to invest in railway modernization. Investing in extensive or one-time upgrades to the railway network will improve efficiency while encouraging the modernization of critical components to overcome systemic issues. Expansions in the handling facilities and transshipment activities, yard areas, and railway infrastructure to optimize operations and transit times and enhance service quality. It also reduces maintenance over the years, increases safety, and increases capacity for the rail sector, resulting in more dependable and competitive services. This investment strengthens the railway system and, subsequently, the economy by ensuring the seamless and faster movement of goods and individuals. Moreover, Mongolia's railway sector's sustainable development is expected to significantly influence rolling stock improvements and technological innovation, attract international funding, and facilitate investment in new railway projects.

A limitation of this study is that the data used in the study was not the most recent, but data from 5 years ago, so recent efficiency analysis was not possible. This is because the open data of the CAREC railway sector released by the Asian Development Bank was published in 2021, but the data is from the previous year. In addition, there has yet to be a recent report from ADB. Another expected research topic in the future is a study on specific strategies for Mongolia to reduce operating costs and improve operating efficiency, and among the CAREC countries that were compared and analyzed in this study, benchmarking the efficient frontier or analyzing alternatives through AHP analysis would be effective.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Coffee beans special handling: analysis the cost of hinterland freight transport

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Keywords: coffee beans, freight transport, hinterland transport, logistics, transportation cost.
Abstract: Indonesia has the second largest coffee plantation in the world, but as an exporter, Indonesia has a lower comparative advantage than its competitors. Internal transportation costs play a significant part in this issue. In previous research on internal transportation costs, maintaining the quality of the commodity during transportation and what resources are needed to maintain it has not been explicitly discussed. Coffee beans categorized as hygroscopic are not included in the perishable commodity category. Hence, special handling is not required in the transportation, but this process may decrease its quality. This research aims to determine the structure of transportation costs in coffee bean export in West Java. It considers the resources (costs) related to the special treatment required to maintain quality. Thus, the quality of the commodity can be maintained until it reaches Tanjung Priok Port. This research used the Activity-based Costing method, which is claimed to be more accurate than traditional costing. The results are that in the hinterland transport for the coffee export, apart from the cost of travel, handling at the port, and loading and unloading, shippers pay special treatment costs, namely packaging and containers, so that the quality of the coffee can be maintained. The special treatment costs required are 80% of the total transportation costs from the processor to the consolidation point/dry port and 26% of the total transportation costs from the consolidation point/dry port to the Tanjung Priok Port.

1 Introduction

Indonesia has the second largest area of coffee-producing plantations in the world. Still, as a coffee exporter, it is only the fourth largest. This represents the potential for re-development of the coffee industry if productivity can be increased [1]. The trade performance of Indonesian coffee products in terms of competitiveness compared to other countries such as Colombia, Vietnam, and Brazil has the lowest RCA value. The RCA (Revealed Comparative Advantage) measures the country's competitive strengths for exporting goods. It means that Indonesia has a lower comparative advantage compared to other countries [2-5]. Several researchers have studied the factors that can influence export activities. They state that there is a relationship between internal freight transportation costs and export competitiveness [6-10]. Freight transportation costs have an impact on international trade, whereas increasing freight transportation costs harm exports [11-15].

To maintain competitive status, companies must be able to provide high-quality services/products in the shortest time at the lowest possible cost [16]. Accurate cost information is essential for every aspect of the business to deliver lower costs, influencing pricing policies and performance reviews [17]. One factor influencing competitiveness and income is price, where one of the price-makers at the farmer, trader and exporter level is transportation costs (Figure 1).

Coffee commodities are hygroscopic, which means they can absorb water molecules from their environment [18]. [19] states that damage to goods can occur during pre-processing, processing and packing, storage, transportation and marketing. [20] stated that coffee beans are easily exposed to various microbial contaminants during cultivation, harvesting, processing, transportation and storage. Humidity levels and room temperature can influence the increase in water content during coffee bean storage, which can cause damage [21]. Humidity is one of the factors causing fungal contamination in coffee [22]. [23] stated that Ochratoxin A can grow on dry coffee beans if the coffee beans are stored in an environment with a relative humidity balance higher than 87%. Rapid temperature changes affect humidity and trigger condensation, which, if not handled properly, will cause fermentation [24].

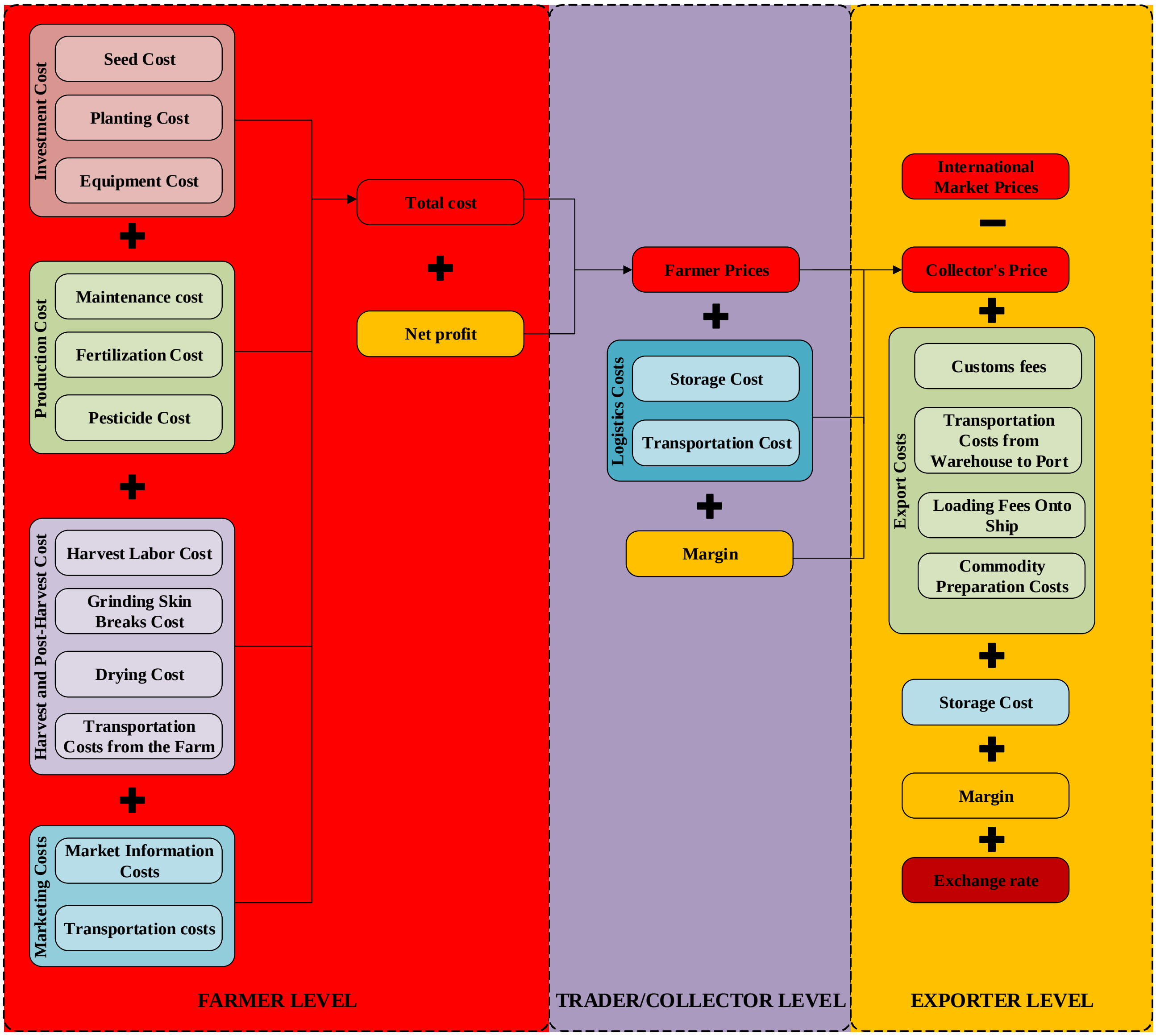

Figure 1 Cost structure and factors forming coffee prices
(Source: Indonesian Competition Commission, 2020)

Condensation is a change in state from gas to liquid. Condensation of a container occurs when the walls of the container become cooler than the dew point of the air inside. Factors influencing condensation include temperature, air space, ventilation, product moisture content and container care/use [25]. Water droplets formed due to condensation inside containers can cause severe damage to the cargo [26]. Requirements for the quality of coffee beans have been stipulated in International Standards and National Standards (SNI 01-2907-2008), which consist of several criteria, including no live insects, no foul smell or mold, the maximum water content of 12.5%, and maximum impurity content 0.5%. In Indonesia, hinterland transportation coffee beans for export uses dry containers, whereas transporting coffee using containers requires paying attention to the temperature factor. The container's temperature during transportation is similar to the warehouse temperature so it can affect the quality of the coffee beans; therefore, a temperature stabilization method is needed.

Therefore, we state our research question as follows: What is the freight transportation cost structure model in coffee bean export activities in West Java that considers resources (costs) related to special handling needed to maintain quality in the transportation process so that the quality of the commodity can be achieved and maintained until the Tanjung Priok Port under the FOB contract. The freight transportation system in this research only examines hinterland transportation because most coffee export contracts use Free On Board (FOB) contracts (Interview results, 2022).

2 Literature review

Research related to freight transport, especially for grain commodities, has been carried out by [27-30] for soybean commodities in Brazil and [31] for coffee commodities in Peru. In previous studies, researchers did not discuss explicitly how to maintain the quality of the commodity during the freight transport process and what resources are needed to maintain the quality of the commodity during the freight transport process. Because coffee beans are not included in the perishable commodity category, the freight transport process does not require special handling. This is certainly different from research that examines freight transport for commodities that fall into the perishable commodity category, such as that carried out by [32] for orange commodities, [33] for fresh fish commodities and [34] for banana commodities, which in their research includes additional resources (costs) required to maintain the quality of these commodities in the transportation process, which can consist of the use of refrigerated containers or deterioration costs/time value.

[33] presented a freight transportation cost structure model consisting of travel costs and deterioration costs/time value related to fresh fish commodities. [35] presents a freight transportation cost structure model consisting of travel, port, and loading and unloading costs. [36] presents a freight transportation cost structure model of travel costs and vehicle utilization. [27] presented a freight transportation cost structure model consisting of travel, loading, and unloading costs. [29] present a freight transportation cost structure model consisting of travel, port, and loading and unloading costs. [32] presents a freight transportation cost structure model consisting of travel costs, port costs, deterioration costs/time value, and special handling costs for citrus commodities. [30] present a freight transportation cost structure model consisting of travel, port, and loading and unloading costs. [37] present a freight transportation cost structure model consisting of travel, loading, and unloading costs.

3 Methodology

3.1 *Indonesian context*

Coffee is one of the grain commodities produced by plantations, which plays a vital role in economic activities in Indonesia and is one of Indonesia's export commodities, which is quite important as a foreign exchange earner besides oil and gas [38-41]. Arabica coffee accounts for around 63% of the international coffee trade, and Robusta coffee around 37% [42].

West Java is the fourth largest Arabica coffee-producing center after North Sumatra, Aceh and South Sulawesi. In West Java, Arabica coffee is slightly more dominant, 59% of the total area and 54% of the total production of smallholder coffee plantations [43]. The Arabica coffee business in West Java is included in the sustainable category. Still, efforts need to be made to improve performance and maintain the sustainability of the Arabica coffee business, one of which is looking for breakthroughs to increase farmers' income [43].

Bandung Regency is the largest coffee-producing region in West Java (32%). [44] stated that coffee commodities have a role in the regional economy, where they are the leading or basic sector at both the Pangalengan District and Bandung Regency levels. Geographically, the Mount Malabar-Pangalengan area of Bandung Regency has a height of 1,400–1,800 meters above sea level, air temperature of 15-21 C, and rainfall of 2,000 mm/year. These conditions, including land and climate, are very suitable for Arabica coffee productivity [1].

Several things caused the fluctuation in the volume of Indonesian coffee exports; the General Chair of the Association of Indonesian Export Companies (GPEI) stated that the reason the performance of non-oil and gas exports to several countries failed to reach targets last year was because the prices of products from Indonesia were not competitive. The cost of authentic Indonesian coffee is higher than that of foreign coffee because some Indonesian coffee is produced by farmers who grow crops in hard-to-reach or remote areas [45]. Factors that influence the quantity of Indonesian coffee exports are the coffee export price (Free On Board price) [46]. This was also stated by [47], where the price of coffee exports had a significant negative influence on the volume of coffee exports to Germany.

3.2 *Hinterland freight transportation flow*

The area of Coffee Plantation in South Bandung - West Java is 3,179.65 Ha (Table 1), where each hectare of plantation area can be planted with 2,500 coffee trees, and each tree can produce 4 kg of Coffee Fruit. The time between flowering and fruit ripening for Arabica varieties in Coffee Plantations in South Bandung - West Java is around seven months. Ripe coffee fruit is known as "Coffee Cherries", a product from farmers to be sold and sent to processors.

Table 1 South Bandung-West Java Coffee Commodity Area

Forest Management Unit Section Area	Coffee Commodity Area (Ha)
Banjaran	944.93
Cililin	36.09
Ciparay	677.77
Ciwidey	319.29
Pangalengan	484.79
Tambak Ruyung Barat	359.66
Tambak Ruyung Timur	357.12
Total	**3,179.65**

(Source: Perum Perhutani, 2022)

Coffee Cherries purchased by processors from farmers are processed by separating the coffee beans from their skin and the fruit flesh and drying them from their initial water content; all coffee beans must be separated from their fruit and dried. There are three techniques used to process coffee: the dry process, or "natural", the wet process (and washed), and a hybrid process called the semi-washed method, or "pulped natural". The coffee produced from this process is called green beans, which becomes an export commodity from processors or exporters.

Figure 2 Map of the coffee farm area in South Bandung-West Java, consolidation point and export ports

We have collected data on activities, productivity, resources, transport facilities, and infrastructure used at the farmer to port levels. Because the plantation location is limited, the freight transport flow from the plantation to the Tanjung Priok Port must go through several stages, and the modes used are shown in Figure 3.

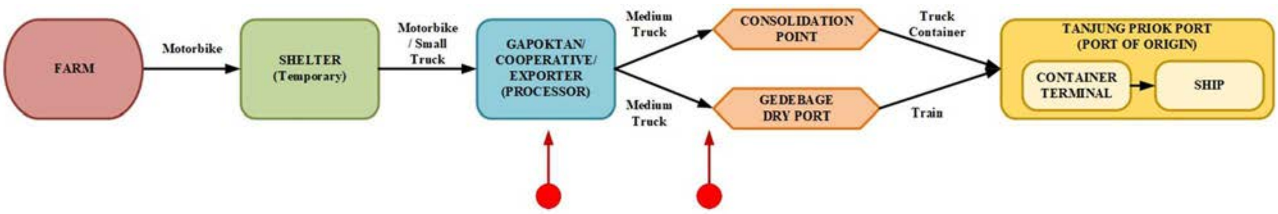

Figure 3 Hinterland freight transport flow for coffee export activity in West Java

3.3 Cost model

Because the coffee commodity is not sensitive to time with a shelf life of >1 year [24] and social, environmental and economic aspects are not taken into consideration by coffee business actors [48], this study does not consider the value of time and external costs. This research focuses only on operational costs because coffee business actors bear these costs.

In this freight transportation cost structure model special handling needs to be included in the freight transportation cost structure model for coffee commodities because this cost is one of the costs that must be incurred/charged (becoming a factor in forming transportation costs) so that the quality of the coffee bean commodity is not damaged/maintained during the transportation process. This is due to the hygroscopic nature of coffee and the presence of condensation [18-24,26,49]. The environmental conditions of coffee producers in West Java, which geographically have an altitude of 1,400-1,800 meters above sea level and an air temperature of 15-21 °C. In contrast, geographically available ports have an altitude below the producers, with temperatures air above the producer, so there is the

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potential for condensation to occur during the transportation process.

The freight transportation cost structure model from the farm (i) to the port of origin (j) for coffee beans is as follows (1):

$$C_{ij} = C_r + C_t + C_p + C_b + C_q \quad (1)$$

Where:

C_{ij}: Freight transportation cost from the farm (i) to the port of origin (j),

C_r: Highway Travel Costs (USD/Ton/Km),

C_t: Train Travel Cost (USD/Ton/Km),

C_p: Goods Handling Costs at the Port (USD/TEU),

C_l: Loading and unloading costs if more than one mode is used (USD/Ton),

C_h: Special Handling Cost (USD/m^3).

4 Results

4.1 Analysis of hinterland freight transportation

Following Figure 3, data collection and processing are adjusted to the freight transportation stages: Stage 1: Farm to shelter, Stage 2: Shelter to processor and stage, 3: Processor to Tanjung Priok Port. Apart from that, some special handling is required in several stages, as illustrated by the red dots. Freight Transportation costs are obtained from interviews and document reviews from coffee business actors. The costs obtained from these processors, exporters, and dry port managers are converted to 1 IDR, which is 0.000065 USD.

4.1.1 Phase 1: Farm to shelter

Table 2 details that the mode of freight transportation that can be used to transport coffee cherries from the coffee plantation to the shelter is a motorbike (see Figure 4) with certain modifications. This is because the type of road used is along an unpaved route with a width of 1 to 2.5 meters, with the distance traveled varying between 30 to 60 minutes according to the plantation area.

Table 2 Characteristics mode and transportation cost from the farm to the shelter

Mileage	± 3 Km
Traveling time	30 - 60 Minutes
Infrastructure Pavement Type	Unpaved, with a width of 1 - 2.5 meters
Type of Facility	Motorbike
Carrying Capacity	160 Kg/Trip
Freight costs	0.033 USD/Kg

Figure 4 Transportation mode from the farm to the shelter (Source: Bintoha Perkoci, 2022)

4.1.2 Phase 2: Shelter to processor

Table 3 details that two alternative modes of freight transportation can be used to transport coffee cherries from the shelter to the processor, namely a small truck (Colt Pickup) and motorbike with the type of road along the paved route (50% asphalt, 50% concrete).

Table 3 Characteristics mode and transportation cost from the shelter to the processor

	Alternative I	**Alternative II**
Type of Facility	Motorbike	Small Truck (Colt Pickup)
Carrying Capacity	80 Kg/Trip	1,500 Kg/Trip
Freight costs	4.87 USD/Trip	22.75 USD/Trip

4.1.3 Phase 3: Processor to Tanjung Priok Port

Tables 4 and 5 detail that in the freight transport process from the processor to Tanjung Priok Port, there are 2 choices. The first is from the processor to the consolidation point using a CDE truck because the characteristics of the road to and from the processor do not allow container trucks to pass through. From the consolidation point, the process of consolidating the cargo from the CDE truck into the container truck is carried out, after which the container truck will carry the cargo to the Tanjung Priok Port. The second alternative is to use a train, where from the processor to the Gedebage Dry Port using a CDE truck and from the Gedebage Dry Port, the process of consolidating the cargo from the CDE truck into a container is carried out, which the container will then carry cargo to the Tanjung Priok Port by train. The Gedebage Dry Port is also used as a consolidation point.

Table 4 Characteristics mode and transportation cost from processor to consolidation point/ Gedebage Dry Port

Type of Facility	CDE truck
Carrying Capacity	2 Tons/Trip
Freight costs	52 USD/Trip
Loading Services	6.5 USD/Trip
Unloading Services	6.5 USD/Trip
Special Handling (Packaging)	6.5 USD/Packaging
Special Handling (Plastic Pallet For Container)	48.75 USD/Trip

Table 5 Characteristics mode and transportation cost from Consolidation point/Gedebage Dry Port to Tanjung Priok Port

	Alternative I (Truck)	**Alternative II (Train)**
Type of Facility	Truck with 20 ft Container	Train with 20 ft Container
Carrying Capacity	19.2 Tons/TEU	19.2 Tons/TEU
Freight costs	234 USD/TEU	39 USD/ TEU
Loading Services	13 USD/ TEU	13 USD/ TEU
Stuffing Costs	-	26 USD/ TEU
Stuck costs	-	3.25 USD/ TEU/day
Pasoso terminal to Port	-	39 USD/ TEU
Special Handling (plastic pallets, containerboard and silica gel)	300.30 USD/TEU	300.30 USD/TEU

4.2 Analysis of hinterland freight transportation cost

Apart from the transportation costs explained in point 4.1, other costs are identified, including handling costs, special handling costs and other related costs at the Tanjung Priok Port.

Table 6 Transportation cost at the Tanjung Priok Port

Custom Clearance Export	409.50 USD/TEU
Surcharge	56.87 USD/TEU
Quarantine Handling	175.50 USD/TEU
Fumigation	97.50 USD/TEU

To answer the research questions, cost calculations were carried out using the Activity Based Costing (ABC) method because the Activity Based Costing (ABC) method is claimed to be more accurate than traditional costing methods. Apart from this, the Activity Based Costing method has few applications in freight transportation activities [16], so it can be a reference for enriching information.

The calculation of freight transportation costs from the plantation to the processor is based on the estimated annual coffee plant production. Where the estimated Coffee Cherries production is based on the productivity of the plantation area, 1 (one) Ha of plantation can be planted with 2.500 coffee trees, where each coffee tree can produce 4 kg of Coffee Cherries.

Freight transportation costs from the farm to the processor are based on the estimated annual coffee plant production, where transportation from the plantation to the shelter is by motorbike, while from the shelter to the processor using two available alternatives as in Table 7, after grouping based on activity level up to with the cost driver, the transportation costs from farm to processor are obtained as in Table 8.

Table 7 Allocation of the activity costs to the cost objects (Farm – Shelter – Processor)

Activity level	Activity	Cost Driver	Number of Cost Drivers
Units	Coffee Cherries Production	Production Volume	31,796,500
Batches	Transportation “Farm – Shelter”	Number of Trips	198,728
	Transportation “Shelter - Processor “ (alternative 1)	Number of Trips	397,456
	Transportation “Shelter – Processor” (alternative 2)	Number of Trips	21,198

Table 8 Total Transportation Cost (Farm – Shelter – Processor)

Activity	Total Cost
Transportation From Farm to Shelter (Travel Cost) “C_r”	1,033,386.25 USD
Transportation From Shelter to Processor (Travel Cost - alternative 1) “C_r”	1,937,599.22 USD
Transportation From Shelter to Processor (Travel Cost - alternative 2) “C_r”	482,246.92 USD

The calculation of freight transportation costs from the processor to the consolidation point/dry port is done based on the estimated green beans production from the processor, where every 1 kg of cherries can produce 0.2 coffee beans. Transportation from the processor to the consolidation point/Gede Bage dry port uses a CDE truck, as in Table 9. After grouping based on activity level up to the cost driver, the transportation costs from the processor to the consolidation point/Gede Bage dry port are obtained as in Table 10 and Figure 5.

Regarding special handling costs, the process of exporting coffee from West Java, especially Bandung district, is carried out by providing special packaging to the product using multilayer recyclable polyethylene plastic (PE) and Gunny suck materials with a capacity of 60 Kg/packaging. (Figure 6). Plastic pallets are added as a base for the truck container to prevent product damage due to condensation during transportation. The use of resources related to special handling is a cost that the exporter must bear, so it must be calculated as an expenditure.

Table 9 Allocation of the activity costs to the cost objects (from processor to consolidation point/dry port)

Activity level	Activity	Cost Driver	Number of Cost Drivers
Units	Green beans Production	Production Volume	6,359,300
Batches	Transportation From processor to Consolidation Point/Gedebage Dry Port	Number of Trips	3,180
	Special Handling (Packaging)	Number of Packaging	105,988
	Special Handling (Plastic Pallets for container)	Number of Trips	3,180
	Unloading	Unloading Quantity	3,180
	Loading	Loading Quantity	3,180

Table 10 Freight Transportation Cost (from processor to consolidation point/Gedebage dry port)

Activity	Total Cost
Transportation From processor to consolidation point/Gedebage dry port (Travel Cost) “C_r”	165,341.80 USD
Special Handling (Packaging) “C_h”	688,924.17 USD
Special Handling (Plastic Pallets for container) “C_h”	155.007.94 USD
Unloading “C_l”	20.667.73 USD
Loading “C_l”	20.667.73 USD

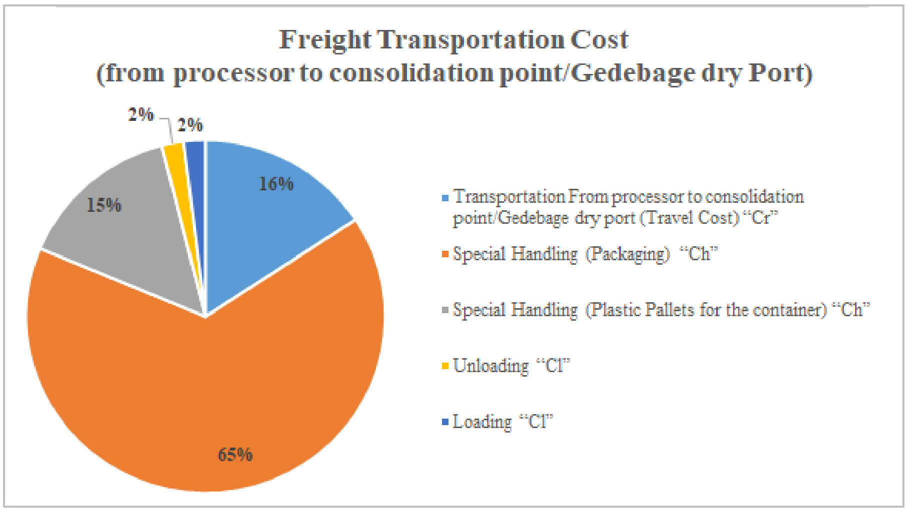

Figure 5 Freight Transportation Cost (from processor to consolidation point/Gedebage dry port)

Figure 6 Special handling (packaging)
(Source: Bintoha Perkoci, 2022)

Calculate transportation costs from the consolidation point/dry port to the port of origin based on estimates of green bean production from the processor, which can use two available alternatives, container trucks or trains, as shown in Table 11. After grouping based on activity level up to cost drivers, transportation costs are obtained from the consolidation point/dry port to the port of origin as in Table 12 and Table 13, Figure 8 and Figure 9.

Regarding special handling costs, in the transportation process from the consolidation point/dry port to the port of origin, to prevent product damage due to condensation that occurs during the transportation process, this is done by adding plastic pallets as a base for the container, lining the inside of the container with containerboard, and use of silica gel (Figure 7). The use of resources related to special handling is a cost that the exporter must bear, so it must be calculated as an expenditure.

Figure 7 Special handling for containers
(Source: Bintoha Perkoci, 2022)

Table 11 Allocation of the activity costs to the cost objects (from consolidation point/dry port to Port of origin)

Activity level	Activity	Cost Driver	Number of Cost Drivers
Units	Green beans Production	Production Volume	6,359,300
Batches	Transportation From Consolidation Point to Tanjung Priok Port (Alternative 1 "Truck")	Number of Trip Containers (TEU)	331
	Transportation From Gedebage Dry Port to Tanjung Priok Port (Alternative 2 "Train")	Number of Trip Containers (TEU)	331
	Special Handling (plastic pallets, containerboard and silica gel for container)	Number of Trip Containers (TEU)	331
	Loading	Number of Trip Containers (TEU)	331
	Custom Clearance Export	Number of Trip Containers (TEU)	331
	Surcharge	Number of Trip Containers (TEU)	331
	Quarantine Handling	Number of Trip Containers (TEU)	331
	Fumigation	Number of Trip Containers (TEU)	331

Table 12 Total Transportation Cost (from consolidation point/dry port to Port of origin) Alternative 1 "Truck"

Activity	Total Cost
Transportation From Consolidation point to Tanjung Priok Port (Travel Cost) "C_r"	77,503.97 USD
Special Handling (plastic pallets, containerboard and silica gel for container) "C_h"	99,463.43 USD
Loading "C_l"	4,305.78 USD
Custom Clearance Export "C_p"	135,631.95 USD
Surcharge "C_p"	18,837.77 USD
Quarantine Handling "C_p"	58,127.98 USD
Fumigation "C_p"	32,293.32 USD

Table 13 Total Transportation Cost (from consolidation point/dry port to Port of origin) Alternative 2 "Train"

Activity	Total Cost
Transportation From Gedebage Dry Port to Tanjung Priok Port (Travel Cost) "C_t"	35,522.65 USD
Special Handling (plastic pallets, containerboard and silica gel for container) "C_h"	99,463.43 USD
Loading "C_l"	4,305.78 USD
Custom Clearance Export "C_p"	135,631.95 USD
Surcharge "C_p"	18,837.77 USD
Quarantine Handling "C_p"	58,127.98 USD
Fumigation "C_p"	32,293.32 USD

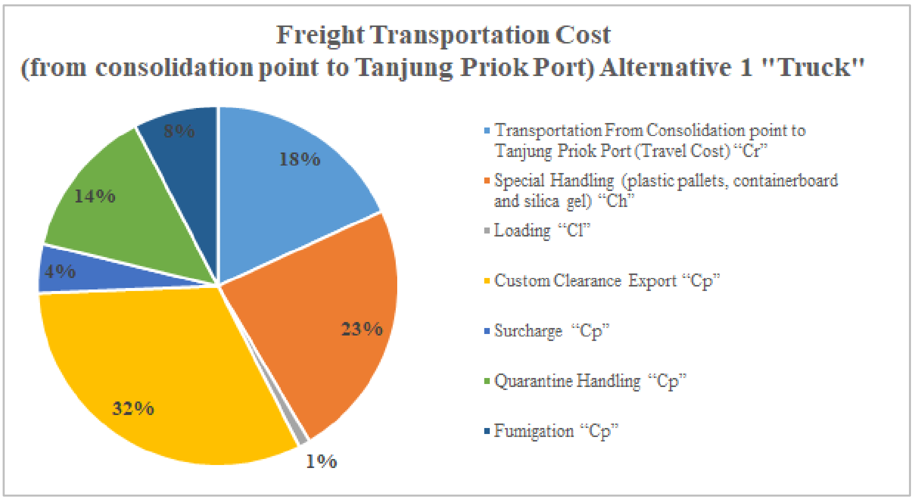

Figure 8 Freight Transportation Cost (from consolidation point to Tanjung Priok Port) Alternative 1 "Truck"

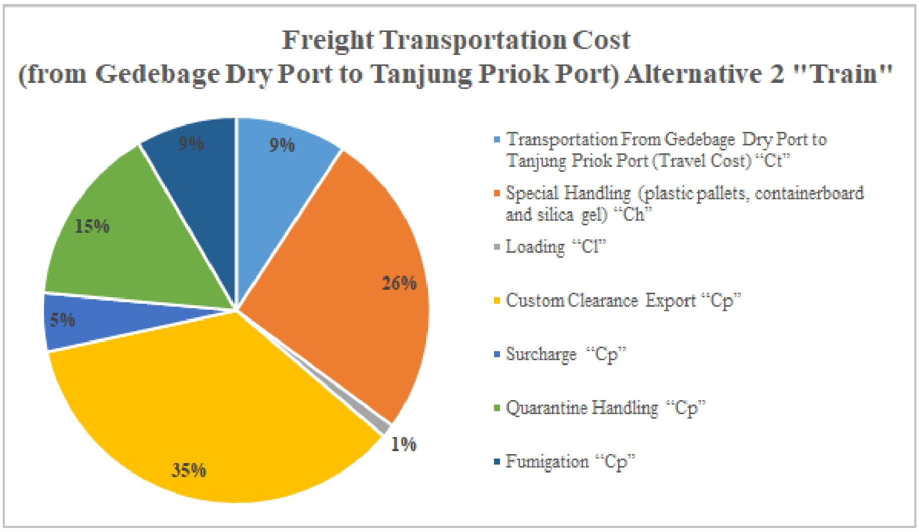

Figure 9 Freight Transportation Cost (from Gedebage dry port to Tanjung Priok Port) Alternative 2 "Train"

From the results obtained, it can be seen that in the transportation process from farm to processor, the transportation costs that arise are only related to travel costs. In contrast, in the transportation process from processor to consolidation point/Gedebage dry port, the shipper must bear transportation costs consist of costs. Travel costs are 16%, special handling costs related to packaging are 65%, special handling costs related to containers (plastic pallets for container) are 15% and loading and unloading costs are 4%. These packaging costs arise because of the export destination. They will differ from domestic deliveries, where the packaging required for domestic deliveries is more straightforward.

In the transportation process from the consolidation point/Gedebage dry port to the Tanjung Priok Port, the transportation costs that must be borne by the shipper using truck mode consist of travel costs of 18%, special handling costs related to containers (plastic pallets, containerboard and silica gel) of 23%, loading and unloading costs of 1% and the rest is port fees. Likewise, the train mode consists of travel costs of 9%, special handling costs related to containers (plastic pallets, containerboard and silica gel) of 26%, loading and unloading costs of 1% and the remaining port costs.

5 Discussion

To answer our research question, 'What is the freight transportation cost structure model in coffee bean export activities in West Java which considers resources (costs) related to special handling needed to maintain quality in the transportation process so that the quality of the commodity can be maintained until it reaches Tanjung Priok Port under FOB contract', the results of this research are that in the hinterland freight transport process for exporting coffee commodities, apart from travel costs, container handling costs at the port, and loading unloading costs, exporters must pay special handling costs to ensure the quality of the commodity Coffee can be maintained at the port of origin and protected from condensation, where these costs consist of special handling costs for packaging and special handling costs for containers including plastic pallets, containerboard and silica gel.

In the freight transport process from the processor to the consolidation point/Gedebage dry port, the special handling costs required are 80% of the total transportation costs. This is related to the packaging costs of 65% and the special handling costs associated with the container of 15%. While in the transportation process from the consolidation point/Gedebage dry port to the Tanjung Priok Port, for the mode of transportation by truck or train, the special treatment costs related to the container are 23 to 26% of the total transportation costs. The difference is because the travel costs using trains are 46% cheaper than using trucks.

So even though the green beans commodity is not a perishable goods commodity, in the freight transport process, it is necessary to include costs related to activities required to maintain the quality of the goods (special handling) so that the freight transport process does not cause a decrease in quality/damage to the goods due to condensation and the green beans commodity hygroscopic in nature. Special handling costs arise when the product is green beans, starting from the shipping process from the processor to the Tanjung Priok Port. Regarding the choice of mode, train travel costs are slightly cheaper than trucks; this is in line with research results [50-52].

6 Conclusion

The main concern of this research is to provide information regarding the need for special handling costs in transporting green beans for export purposes so that it can be a consideration for business actors. To achieve this goal, we calculated freight transportation costs; from the calculation results, it was found that in green bean transportation activities for export purposes, expenses related to travel, loading and unloading costs, handling costs at the port, and special handling costs were required.

This research contributes to theory and practice. In terms of theoretical contribution, our study confirms that even though green beans are not a *perishable goods* commodity, the transportation process needs to include costs related to activities required to maintain the quality of the goods (special handling), where up to now the costs of maintaining the quality of the goods have been focused only on *perishable goods commodities.* In terms of practical contribution, our research provides information to coffee exporting business actors that the special handling costs incurred by business actors are pretty large, around 80% of the total transportation costs during the transport process from the processor to the consolidation point/dry port and around 23% to 26% of the total transportation costs during the transport process from the consolidation point/dry port to the port of origin, so business actors need to look for other alternatives to be more efficient.

Transportation using trains is more efficient than highways. Besides, it can reduce traffic flow volume, highway congestion and emissions. Therefore, the government should reactivate the railway line from Gede Bage to Tanjung Priok and carry out unique strategies so that trains from Gede Bage Dry Port to Tanjung Priok Port can be more attractive to coffee business actors. This research has limitations. One of the limitations is that this research does not consider various alternative tools or methods that can be used to maintain the quality of goods (special treatment) so that the transportation process does not cause a decrease in quality/damage to goods such as the use of Fantainers.

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ICT diffusion, financial development and manufacturing propel economic growth in GCC nations: does panel data model provide new evidence?

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Keywords: Diffusion of Information and Communication Technology - ICT diffusion, financial development, manufacturing, economic growth, Gulf Cooperation Council countries - GCC.
Abstract: This study seeks to investigate how financial development, manufacturing and the access and diffusion of information and communication technology (ICT) add value to economies within the Gulf Cooperation Council countries (GCC). Precisely, it is supposed to explain how variables facilitate regional development and economic growth individually and jointly. In this context, the objective of the present study is to shade light on how financial development, Manufacturing and ICT dissemination impact regional economic performance and sustainability, analysing their interactions. The analysis of the variables affecting GDP per capita in the GCC nations throughout during 2001 to 2021 was performed using a panel data model estimation technique. The study at hand attempts to probe the present frame of financial development functions and ICT dissemination, among other economic factors, along with their interaction in influencing regional economic growth and development. In this regard, Financial Development, Manufacturing and ICT diffusion have a positive significant impact on the GDP per capita of the GCC countries; the fact that financial support and access to ICT highlight the major part played in the development of the economy. On the contrary, Manufacturing imparted a minor effect on the GDP, as revealed by its relatively low coefficient of correlation estimated at 0.614. The findings of this study will add new critical information to the scholars, researchers, and policy analysts concerned with the study of ICT, financial development, and economic growth in the GCC. This study merges the impact of financial development and ICT diffusion on regional economic growth by testing the relationship in a new dimension.

1 Introduction

Diffusion of ICT enhances the aspects of productivity, information availability, and connective abilities across sectors, all those factors that have a great impact on economic growth. Inclusion of the marginalized sections of the population, reduction of transaction costs, and inclusiveness-all these have been effectively facilitated by internet and mobile technological development. It further facilitates access to international markets, healthcare, and education, fosters innovation, and enables economies to make use of a networked world [1]. This again supports the fact that growth in both developed and developing countries is influenced by expanding ICT, though more research might be needed concerning the future impact in those regions where technology is being adopted at an increasing rate currently [2].

Through the above, we find that there is a strong relationship between the spread of information and communication technology and Manufacturing and financial development, which in turn enhances the economic growth of any country, and many developing countries and the Gulf Cooperation Countries seek to develop their financial sector and manufacturing policy using information and communication technology to enhance economic growth. Many scholars have also addressed in recent years the impact of the spread of information and communication technology on economic growth, from the role played by information and communication technology in accelerating production processes, organizing management, and contributing to reducing costs, which in turn is reflected in the development of companies and thus increasing employment and stimulating consumption and thus raising economic growth rates. This is proven by economic theories, but on the part of applied studies, there are studies that have agreed with economic theory, the most important of which are [1,3,4] and other studies. There are other studies that did not agree with economic theory and found negative effects, including [5-9] and other studies.

In the Cobb-Douglas model the underlying economic theory is that the three major inputs, namely, labour, capital, and technology, combine to form the total production function and thus contribute towards economic growth. Accordingly, in these production conditions, financial development is usually considered to represent the capital, and manufacturing policy is labour, while ICT represents the technological advance. The financial sector alone makes resource allocation more effective through savings mobilization, directing resources to high-productivity investments, reducing information costs and transaction costs that facilitate interindustry trade. Resource allocation is also more effective when there is saving mobilization, directing resources to high-productivity investments, information cost reductions, and transaction cost reductions facilitating interindustry trade as also noted by [10-12]. In this regard, acceleration in money and technology accumulation leads to overall development. Yet, the 2008–2009 financial crisis brought into focus how defective financial institutions can lead to resource misallocation, speculation, underinvestment, and waste. The empirical evidence shows that financial development has brought mixed and sometimes adverse effects on growth, often linked to increased financial crises, thinness of the stock market, or nonlinearities in the relationship between [13-16].

The importance of this study is to understand how the common forces of financial development, industrialization, and ICT proliferation affect GCC economic growth by analyzing these factors as complementary drivers of sustainable growth. Overall, financial development, manufacturing, and ICT are critical to diversifying the economy, increasing productivity, and transforming GCC economies from oil dependence to knowledge-based economic structures. This puts ICT in a strategic position to accelerate e-commerce, innovation, and productivity. In any case, financial development reinforces the role of ICT's spread in providing access to capital across the economy, improving investment efficiency, and promoting entrepreneurship, especially through recent developments in digital banking and financial technology (Fintech). These techniques provide financial inclusion, enabling individuals and SMEs to access finance as part of the formal economy, thus integrating larger segments of the population into the economic process. SMEs' access to finance as part of the formal economy, thus integrating larger segments of the population into the economic process.

The study contributes in two ways: first, by considering the mutual dynamics between financial development, manufacturing and ICT in driving economic growth within the GCC; second, by establishing how such sectors together support resilience, growth, and diversification. To that end, this paper addresses some very important questions related to the interrelationship between financial infrastructure, manufacturing and ICT development and their overall impact on economic stability and transformation within GCC countries. Given the drive of the region's policy for diversification, these findings bring to the fore the centrality of ICT-enabled financial services in strengthening the economies of GCC countries against external shocks-such as turbulence in oil prices. These are timely and impactful insights, given that the strategies of GCC countries are oriented toward life in a post-oil future.

The research also makes a policy contribution by underlining the interaction between financial development, manufacturing and ICT diffusion in providing actionable insights for policymakers articulating comprehensive strategies leveraging these factors to improve the resilience and global competitiveness of their countries. The study underscores the need for policy action to promote sustainable growth and diversification in the GCC, and ICT infrastructure development and continued financial sector reforms can improve economic performance, improve living standards and increase employment opportunities for the region's citizens. Second, in pursuit of financial inclusion, it points toward a mechanism of integrating the excluded that can bring about well-balanced and inclusive growth. It has finally been made clear in this paper that regional cooperation in the fields of financial sectors, manufacturing sector and ICT diffusion are one means of ensuring innovation, stability, and sustained economic growth in GCC. Using shared resources, knowledge, and technology, GCC countries can work together to create robust, diversified economies capable of dealing with the changing global economy, thus benefiting the region at large. This should serve as a driving force for regional integration and further encourage investment in cross-border ICT projects, financial networks, and economic partnerships across the GCC region.

This paper is organized into six sections; the first section being the introductory part that puts the study in context, the second constitutes the literature review necessary for the background and identification of gaps in the previous literature, the third presents a description of the methodology adopted for conducting this study, while the fourth section sets forth the findings. The discussion section finally interprets the results, while in the conclusion, after summarizing the salient points and their implications, the reader is provided with a comprehensive framework in which to place the contribution of the study and any possible future research directions.

2 Literature review

Diffusion of information and communication technology, or ICT, along with financial development, represents the most vital components of contemporary economic growth for a wide variety of regions. Although various studies evidence that both ICT and financial development contribute positively to economic growth, their impacts differ according to geographical and economic contexts. In comparison, financial development variables tend to be much stronger in their positive impact on the rate of economic growth in developed economies than the ICT indicators suggest. The financial system furthers one of the imperative functions: the effective allocation of capital funds to foster entrepreneurship and investment, thus stimulating economic growth. However, the role of ICT can be less pronounced for high-income countries, since their economies already have appropriate infrastructures related to technologies.

On the contrary, for economies like the WAEMU countries, the diffusion of ICT is very important for economic growth, considering that its channels of diffusion are mainly through mobile and internet penetration. An investigation by [17] established that the direct contribution of financial development to economic growth was relatively negative, whereas its spillover effect through ICT diffusion impacts economic growth positively, especially beyond a threshold level of penetration. The tendency here is that possible eventual adoption of ICT may help offset initial economic setbacks from financial development in developing economies through productivity and market accessibility as connectivity improves.

The various works conducted on BRICS economies showed that the inter-play between ICT and growth is dynamic in nature. According to [18], subscription to both mobile cellular and fixed broadband exerts an immediate positive impact on growth, while other categories of ICT-related expenditure such as research and development and imports of ICT goods yields growth benefits long-run. Thus, this distinction suggests that while ICT infrastructure catalyzes near-term gains, investments in technology and innovation-like research and development contribute to sustainable economic expansion in the long run. These results once again underscore the need for a balanced approach to ICT investments, with both infrastructure development and continuous innovation.

Nuancing this view in Asian developing economies, it seems that growth is affected by the interaction of ICT with financial development. [1] observe that even though the mere diffusion of ICTs tends to be economically destructive in the short run due to costs and structure adjustments, their integration with financial development results in substantial economic benefits. This is reasoned on the complementary functions of ICT and finance in that finance supports projects brought forth by ICT that in turn enhance economic activities and markets. Therefore, this synergy goes to help in bringing out the relevance of integrating ICT investment strategies into the growth of the financial sector for optimal economic outcomes.

Aggregately, these studies emphasize the interdependence among the variables of financial development and dissemination of ICTs and economic growth; hence, a need to exploit them jointly toward sustainable economic development. Specific country contexts and their comparison sections show several results presented by various researchers: For instance, [19] find a very strong positive interaction between financial development and ICT diffusion within the MENA region, which supports the positive role that ICT would have played in economic growth. [20], however, note that though ICT improves GDP within countries inside MENA, financial development sometimes has adverse effects, underlining regional variability in outcome. [21] argue that the spread of ICT in WAEMU has a positive impact on growth, while financial development has a negative impact. The work of [22] is broader because they assess growth fluctuations. They observe that the diffusion of ICT exerts a positively significant impact on the level and stability of economic growth, thus implying that ICT might also be one more factor contributing to economic resilience in turbulent regions. At the same time, country-specific research provides unique insights. This is what [23] pointed out where the study concluded that ICT and technological innovation in Turkey negatively affect financial development, while the study confirmed that globalization and economic growth positively affect the financial sector. Such inconclusive results simply underpin the differential impacts of ICTs on economic growth across different national contexts. Other studies highlight partial aspects of the impact of ICTs on economic growth. For instance, in Saudi Arabia, [24] indicate that ICT diffusion has a positive moderation role in financial development-economic growth nexus, hence suggesting that ICT can further enhance the growth-enhancing role of financial development. In Malaysia, [25] show that electricity consumption and hence the underlying critical infrastructure are related to ICT growth. The study conducted by [26] on Chinese cities confirms that ICT fosters technological advancement as well as urban efficiency and the benefits from the ICT are almost unaltered by geographical distances. It is from such findings that the impacts of the ICT on economic development essentially manifest that while economic development may be generally fostered by ICT, the regional and structural factors often become essential determinants of the magnitude and nature of impacts.

The broad research indicates interlinkage that is multi-dimensional between financial development, ICT diffusion, and economic growth. Results concerning financial development, however, tend to be mixed and often depend on regional and economic conditions. Whereas it is possible, for example, that financial development may, at times, lag growth or even detract from it, the diffusion of ICT is likely to create more immediate benefits in emerging economies. On the other hand, financial development tends to be positive in relatively more developed countries, which is basically supported by well-established capital markets and regulatory frameworks that are usually rather stable. The complementary role of ICT in the process of financial development further underlines the importance of technological improvements for economic development.

Notwithstanding these findings, the variations across studies do suggest that further research is indeed called for regarding how these relationships work out in their dynamics and policy implications in diverse contexts. It thus appears that the interactions between ICT, financial development, and economic growth can be complex and often dependent on a set of various factors such as infrastructure, regulatory support, and economic maturity.

In this respect, the integration of AI in ICTs and financial systems in the GCC countries could certainly be regarded as one of the giant leaps forward. AI acts as a catalyst for economic development within the GCC region through an increased speed and reach of its financial services. Examples include [18], who review how AI increases the contribution of ICT to the economy, which then turns out to be an important tool for both banking and general economic strategy in the GCC region. This would further increase financial inclusions through artificial intelligence-driven solutions in ICT and increase the quality of service, thereby giving rise to sustainable growth within the economy. This can be a certain transformation that could be seen within regional economies themselves with the advent of such technologies.

3 Data and methodological framework

This section delineates the methodology of the study, a statistical analysis of variables involved, and sources from which the data has been gathered.

3.1 Data and summary statistics

Prior to model construction, we evaluated the expected impact of each study variable, obtaining background knowledge from the World Bank's World Development Indicators. A summary of the same is given in Table 1.

Table 1 Descriptions of variables and the sources of data

Type	Acronym	Description	Source
Dependent Variable	**LnGDPpc**	Gross Domestic Product per capita (constant 2015 US$)	**World Development Indicators (WDI)**
Independent Variables	**LnFD**	Domestic credit to private sector by banks (% of GDP)	
	LnICT	ICT Diffusion: Internet Penetration Rate (Individuals using the Internet (% of population) or Mobile Phone Penetration (Mobile cellular subscriptions (per 100 people).	
	LnMANF	Manufacturing, value added (% of GDP)	

Note: All data available at (DataBank | The World Bank) [27].

Figure 1 shows the trends in ICT Diffusion, financial development, and Manufacturing as drivers of economic growth in GCC nations. The level of ICT Diffusion has gone up gradually during the period, indicating substantial investments in digital infrastructure and connectivity. The financial development has been oscillatory in nature, with rapid growth combined with modest declines probably dictated by global economic conditions and adjustments in policy at the regional level. Manufacturing, too, has shown mixed trends where spells of stability have been interspersed by short-term spikes due to changes in oil prices and external shocks in the economy. Put all these together, and one gets the economic growth trajectory for the GCC economies: an interesting dynamic between technological progress, expansion of financial markets, and price stability comes into play. The figure below shows that ICT and financial policies remain important complements to sustained economic development, particularly in those resource-dependent economies transitioning toward more diversified and knowledge-based growth.

This perhaps has something to do with the way GCC economies have adopted innovation and investment as drivers for growth across major sectors in the economy. Most specifically, the pursuit of ICT Diffusion and financial development has been pursued as mutually reinforcing enablers that can accelerate economic transformation. Integration of ICT enhances efficiency and productivity across industries, while financial development supports capital allocation and innovation. These dynamics have an added layer of significance in the GCC in view of efforts towards de-oil dependence and setting up knowledge-based economies. Second, investment patterns and consumer behaviour could be impacted by inflationary pressures, typically induced via global energy costs and fiscal policies in too many domestic economies. The interaction of Manufacturing with financial development and diffusion of ICT shows how these factors interact in determining sustainable growth trajectories. The emphasis that GCC countries place on digital infrastructure and financial reforms constitutes a strategic commitment to economic resilience and adaptation within global economic currents.

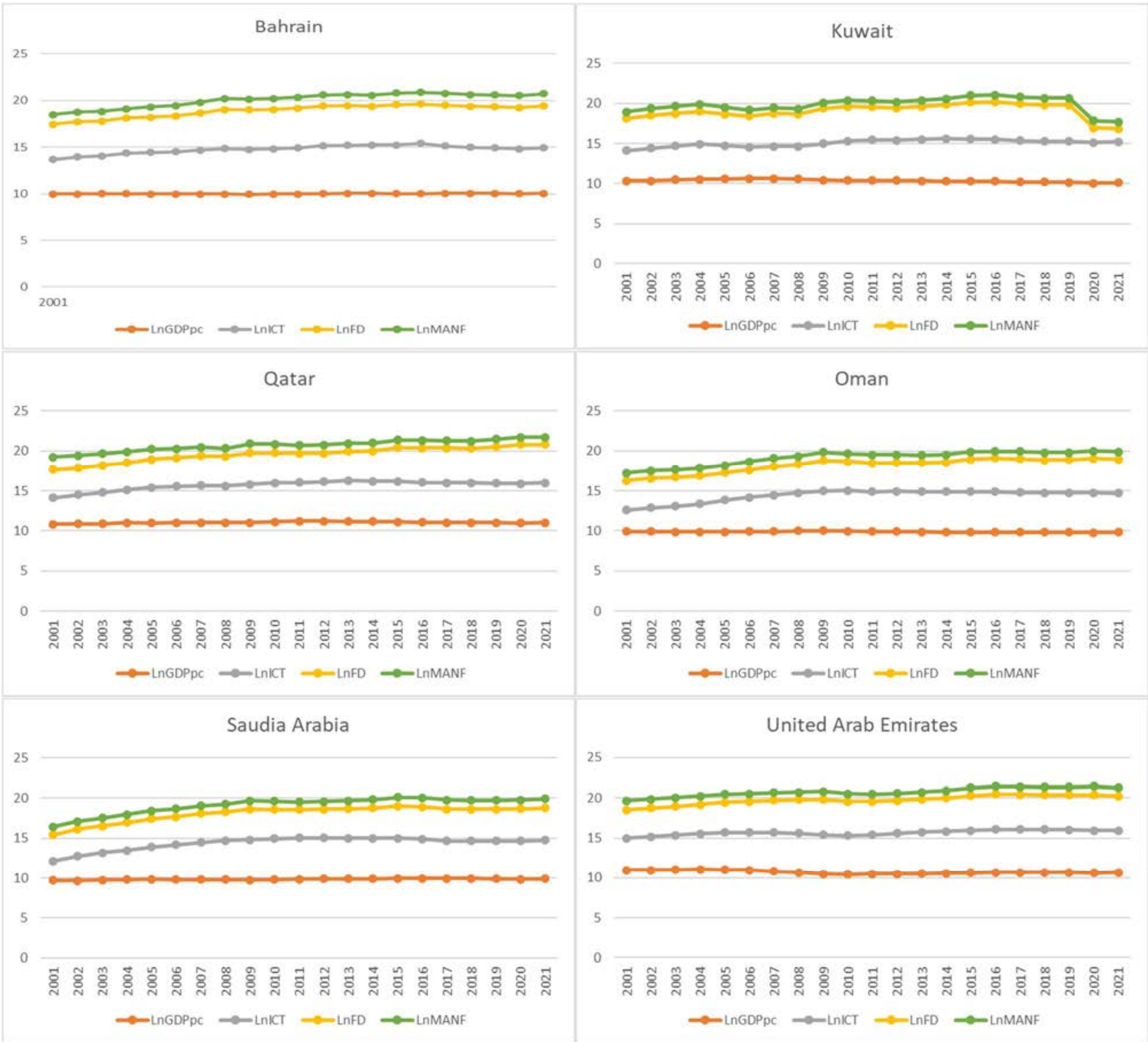

Figure 2 Variable plots

3.2 *Research methodology*

The approach in undertaking any research is well-structured in the delivery of correct and reliable results. First, there is the presentation of data and descriptive statistics as a way of giving a sneak peek into the dataset for describing means, variances, and distributions. In this respect, a correlation analysis will then be implemented showing the relationship of these variables for either multicollinearity or significant associations. Estimation incorporates appropriate econometric techniques, which quantify the relationships and test hypotheses. Diagnostics After estimation, diagnostics are done that verify the validity of the model and its underlying assumptions of normality, homoscedasticity, and no autocorrelation. The result interpretation therefore provides an explanation of findings in the context of the research objectives. Then, different specifications or methods could be performed to check the robustness of results. Results are then compiled, organized in a systematic manner, and summarized into reports that clearly present the findings in concise ways (Figure 2).

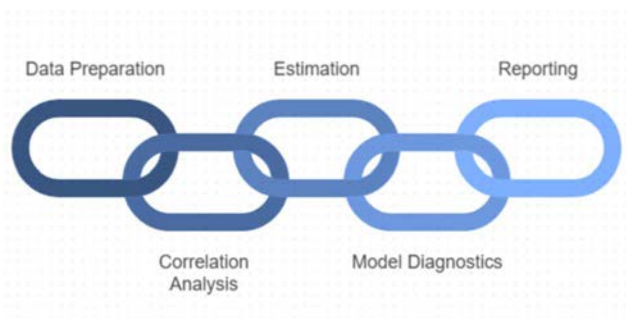

Figure 2 Statistical analysis process

3.3 Specification of the model

This model is specified in a functional form as outlined below. It presents the relationship between the major variables and parameters in the given framework of analysis:

$$LnGDPpc_{it} = \beta_0 + \beta_1 * LnICT_{it} + \beta_2 * LnFD_{it} + \beta_3 * LnMANF_{it} + \varepsilon_{it} \quad (1)$$

Where:
$LnGDPpc_{it}$ - Logarithm of Gross Domestic production Product per capita in country *i* at the time *t*.
$LnICT_{it}$ - Logarithm of Mobile cellular subscriptions (per 100 people) in country *i* at the time *t*.
$LnFD_{it}$ - Logarithm of Domestic credit to private sector by banks (% of GDP) in country *i* at the time *t*.
$LnMANF_{it}$ - Logarithm of Manufacturing in country *i* at the time *t*.
ε_{it} - error term.

3.4 Correlation assessment

From Table 2, it is observable that LnGDPpc is weakly correlated with LnICT, LnFD, and LnMANF. This implies that there is no significant relationship between the variation in LnGDPpc with LnICT, LnFD, and LnMANF. Besides, LnICT is also weakly negatively related to LnMANF but strongly positively related to LnFD. This suggests that large values of LnICT are weakly associated with lower values of LnMANF and strongly associated with high values of LnFD. Also, as it were, there is a moderate negative association of LnFD with LnMANF such that with an increase in LnFD, there is a tendency of LnMANF to reduce.

While these correlations provide insight into the relationships between variables, it must be kept in mind that not all correlations imply causation. Further analysis, such as regression analysis, would be required to establish the nature and intensity of these correlations (Table 2).

Table 2 Matrix of correlation

	LnGDPpc	LnICT	LnFD	LnMANF
LnGDPpc	1.000			
LnICT	0.098	1.000		
LnFD	0.140	0.401	1.000	
LnMANF	0.016	-0.112	-0.143	1.000

3.5 Descriptive statistics

Table 3 following is the descriptive statistics table showing the per capita GDP, the diffusion of ICT, financial development, and manufacturing for various variables.

Table 3 Descriptive statistics

	LnGDPpc	LnICT	LnFD	LnMANF
Mean	10,308	4,68	3,94	1,012
Median	10,071	4,895	4,01	0.988
Max	11,204	5,399	4,93	1.565
Min	9,652	2,437	1,614	0.645

The descriptive statistics for the four variables used are presented in the table below. Starting with descriptive statistics, the average is 10,308 for per capita GDP, LnGDPpc, ICT diffusion with 4.68, financial development at 3.94, and Manufacturing at an average of 1.694. Having Manufacturing = 0.988, ICT = 4.895, financial development = 4.01, and per capita GDP = 10,071, the medians are also close in value to their respective means, indicating a distribution symmetric. The minimum values are 9,652 for per capita GDP, 2.437 for ICT, 1.614 for financial development, and 0.645 for Manufacturing, while the maximum values reached 11,204 for per capita GDP, 5.399 for ICT, 4.93 for financial development, and 1.565 for Manufacturing.

4 Results and discussion

The study also evaluates regression results using fixed-effects and GLS methods. Application of Breusch and Pagan's Lagrangian Multiplier Test on the suitability of random effects would result in the robustness of panel data dynamics analysis.

4.1 Regression analysis: Fixed-Effects method

From these results, 94% of the variation among the entities is explained by the model. Prob > F = 0.0045 implies that the overall model is significant, and hence, all the predictors combined have a significant effect on LnGDPpc. LnICT and LnFD are statistically significant at 1%, which indicates that both variables have a positive contribution to LnGDPpc. However, the coefficient of LnMANF is statistically insignificant. This leads us to believe that LnGDPpc is not significantly different for this model. Table 3 shows that most of the variance can be contributed by the differences between entities with a high rho value of 0.85 (Table 4).

Table 4 Results of Fixed-Effects regression

	Coef	T	P-value
Constant	2.531	1.363	0.026
LnICT	3.412	6.074	0.002
LnFD	6.054	3.742	0.005
LnMANF	3.143	0.452	0.067
R-sq	0.94		
Obs	126		
N group	6		
P-Value	0.0045		

$$LnGDPpc_{it} = 2.531 + 3.412*LnICT_{it} + 6.054*LnFD_{it} + 3.143*LnMANF_{it} \quad (1.1)$$
$$(0.026) \quad (0.002) \quad (0.005) \quad (0.067)$$

The regression results show that ICT Diffusion and FD are both strong drivers of GDP per capita; their highly positive coefficients suggest that increasing mobile technology access and better financial services contribute substantially to economic growth. These very low p-values confirm that the relationships are statistically significant, which means the strength and consistency of the impact is evident across the data observed. While the impact of Manufacturing, INF, may be viewed to be insignificant on GDP per capita due to its high p-value, it may imply that Manufacturing stays within manageable levels such that its distortionary impact on economic productivity is minimal, or that the inflationary pressures balance with other macroeconomic policies or structural factors in the observed economies. Combined results point to technological diffusion and financial development as the most relevant determinants of economic performance, while the role of Manufacturing is less important within the same context.

4.2 Regression analysis: Random Effects

The results indicate that the model explains 52.3% of the difference within the area under study, reflecting a balanced interpretive power. There is overall importance to the model through Prob > chi 2 = 0.052, which means that the combined indicators have an impact on economic growth. The coefficients for LnICT (ICT Diffusion) and LnFD (financial development) are statistically significant at the 1% level and positive. This underlines their significant contribution to per capita GDP growth and validates the hypothesis that technological change and financial development are positively linked to economic performance due to their effects on productivity, innovation, and resource allocation.

However, Manufacturing (LnMANF) is not statistically significant in this model, which may mean that the region's Manufacturing rates remain within an acceptable range or that another factor mitigates its potential negative effects. The R value of 0.614 means a large part of the variation is taken by the variability between entities rather than by variability within entities over time. One would, therefore, say that individual-level attributes or entity-specific features, such as institutional frameworks, economic policies, or structural factors, are crucial determinants of GDP per capita. These findings point out the need for considering cross-entity differences in formulating policies (Table 5).

Table 5 Results of Random-Effects regression

	Coef	T	P-value
Constant	3.123	5.362	0.001
LnICT	6.032	6.253	0.002
LnFD	7.113	3.654	0.005
LnMANF	1.024	8.125	0.050
R-sq	0.614		
Obs	126		
N group	6		
P-Value	0.052		

$$LnGDPpc_{it} = 3.123 + 6.032*LnICT_{t} + 7.113*LnFD_{it} + 1.024*LnMANF_{it} \quad (1.2)$$
$$(0.001) \quad (0.002) \quad (0.005) \quad (0.050)$$

The significant drivers, as shown by the regression analysis, of GDP growth are ICT Diffusion and FD, as reflected by their highly positive coefficients and extremely low p-values. A relationship of this nature is not only strong but also statistically significant, which can be referred to as the fact that increased access to mobile technology promotes communication, productivity, and market efficiency. Moreover, the expansion of credit supply increases the private sector's investment and economic activity. Both factors are critical in stimulating innovation and entrepreneurship, and in the broadest sense there is an economic dynamic.

Conversely, the high probability of INF Manufacturing is associated with little impact on the model's GDP. This may indicate that the level of Manufacturing was stable compared with the data monitored or not high enough to have any significant impact on economic output. Instead, it may refer to mitigating factors in the form of monetary policies or structural flexibility that neutralize the potential impact of Manufacturing.

4.3 Panel data dynamics analysis's sturdiness

Breusch and Pagan Lagrangian Multiplier (LM) test is used to determine whether the random effects model is more suitable than the Oled OLS model. The test also examines the null and void hypothesis that there is no discrepancy between entities (Var (u)), meaning that the random effects model is unnecessary and the Oled OLS model will be more appropriate.

The result of the test, Prob > chibar2 = 0.006, is a p-value less than 0.05, therefore one fails to accept the null hypothesis at 5% significance level or any conventional level. Thus, there is strong evidence to believe that $Var(u) \neq 0$, hence justifying the application of the Random Effects Model. Table 5 provides further illustrations and verifies that the Random Effects Model is an appropriate choice in this analysis because it handles random variation across entities [28].

By failing to accept the null hypothesis, we confirm that there is significant variation across entities, and this in turn supports our assertion that the Random Effects Model is a more adequate model of data. This model provides a better understanding of the impact of forecasters considering the differences between the two entities. Therefore, the analysis of the team's data using the random effects model must be carried out in agreement with the results of the Breusch and Pagan LM test.

Table 6 LM Test (Breusch and Pagan Test)

	Var	Sd-sq (var)
LnGDP	4.756	1.918
E	3.235	4.852
U	2.512	1.714
Chibar 2(01)	856.68	
Prob>Chibar 2	0.006	

5 Conclusions, policy recommendations and study limitations

This paper evaluates the impact of ICT diffusion and financial development, coupled with other economic variables, on GDP growth in GCC nations. It also makes valuable contributions to the growth literature with Fixed-Effects Within and Random Effects GLS regression estimates for major growth drivers in the region. The Fixed-Effects model estimated that the explanatory variables jointly explained 61.40% of the variation in GDP across the GCC nations, the overall significance of the model indicated by a probability value of Prob > F = 0.052. It showed the positive and statistically significant coefficients of ICT Diffusion and FD at the 1% level each, indicating that the factors positively influence the GDP. However, the Manufacturing (MANF) variable was not statistically significant, therefore its contribution to explaining economic growth in this region was minimal.

The very high rho value of 94% for the Fixed-Effects model shows that the country-specific effects, or rather country-to-country differences, explain a large amount of the variation in the GDP. Similarly, Random Effects GLS model also noted an overall significance model of Prob > chi2 = 0.0045. This model further showed that ICT Diffusion and FD had a positive significant effect on GDP at 1 percent while INF remained insignificant. The high R value of 0.94, which shows that entity-specific variations are very significant in influencing such a variable, confirms other results present in the literature and underlines the fact that country-level differences in economic and structural aspects strongly determine growth outcomes.

The Breusch-Pagan Lagrangian Multiplier test indeed confirmed that the application of the Random Effects model would be necessary, as opposed to the Pooled OLS model. In fact, the results of the test reject the null hypothesis of no variance across entities on the grounds of low probability, hence confirming the adequacy of using the Random Effects model. The fact that structural variations across GCC countries significantly influence growth lends credence to the need for addressing peculiar country-level characteristics in economic policy.

From these results, several policy implications arise for the GCC countries. Since mobile cellular subscriptions were found to impact GDP positively, policymakers should invest more in ICT infrastructure, a fact that agrees with the findings of [29], who note that ICT plays a part in the economic transformation. The need exists for policies that would improve digital literacy, enhance internet access, and develop better mobile networks. Also, the positive relationship observed in domestic bank credit to the private sector and GDP would suggest that financial sector policies to expand access to credit and strengthen banking infrastructure may be a good option. Such policies give the private sector an avenue for investment, and thus the economy should be growing and diversifying.

Although the study found that Manufacturing did not affect GDP statistically, it still is a very important economic stability indicator. To this end, low and stable levels of Manufacturing should be maintained by policymakers to facilitate an enabling environment for growth and avoid further any potential hindrances on the economy. The high rho values in both models indicate that country-specific variations significantly explain variations in GDP and suggest that further diversification efforts may be required to create a situation of balanced and sustainable growth in most sectors, reducing dependence on any single sector or resource. Though quite insightful, this study does acknowledge several of its limitations. Analysis is done based on the current availability of data for the GCC region. This data may not be entirely updated or correct or inclusive. Second, enhancing the quality of data and prolonging the time series would make the results more robust. Third, this research relies only on a very limited number of variables: INF, FD, and ICT Diffusion. Other factors might give an even better view of the situation in the economy, such as government policies, geopolitical factors, or state of the world economy. The threat of endogeneity can appear when one of the explanation variables is correlated with an error term, thus yielding biased results. This could, in turn, be the focus of future research that also tries to minimize the problem of endogeneity by using instrumental variables or other econometric techniques.

Results derived from this study may, therefore, not be generalized to regions holding different economic structures, institutional frameworks, and levels of development. The comparison of different regions could provide an even greater perspective on how these relationships could diverge or converge. Moreover, this study focuses on a certain period, and changes in the relationship between variables might change over time. Further studies should analyse whether the same pattern recurs under different economic regimes or time perspective.

Building on this research, future studies should extend the variables of trade openness, government spending, and foreign direct investment to increase the knowledge base that many factors determine GDP growth in the GCC.

More work is required to take care of possible endogeneity, and such findings could be made more credible through robustness checks, using various model specifications. Other comparative analyses with countries or regions may decide whether such patterns might be sustained outside of the GCC context, hence how ICT and financial development would play their roles in different economic environments. More pronounced patterns and points of inflection in longer time-series analyses are likely to yield the impact that the diffusion of ICT and the development of financial industries will have on the economy, particularly since the two sectors are still evolving.

The results of this study point out the important role of ICT diffusion and financial development in reinforcing GDP growth in the GCC countries. This paper provides evidence that ICT infrastructure and financial development are key levers of the process of economic development and, consequently, for reaching economic diversification, private sector investment, and financial inclusion. These will help the policy maker in formulating policies that improve the economic performance, build resilience, and spur sustainable growth in the region. Given the possibility of an improvement in economic resilience facilitated by technology-driven financial services, this is an area which deserves collaborative initiatives by policymakers in pursuit of innovation within the ICT and Financial sectors. This may open diversified economic growth opportunities, decrease reliance on oil revenues, and hence encourage the transition of the GCC toward knowledge-based economies.

The findings of the study further confirm an inclusive approach in how ICT and financial development interact with the structural characteristics of the GCC. Given the emphasis on factors peculiar to the region, the research provides useful empirical evidence in formulating policies aimed at exploiting the potentials of ICT and financial infrastructure as drivers of economic growth. Strategic investment in ICT coupled with appropriate financial policies, therefore, offers a feasible way forward towards sustainable economic development within the GCC.

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