A HEURISTIC-BASED APPROACH TO ENHANCE INTERNAL LOGISTICS TASKS

Mariana RIBEIRO[1], Liliana ÁVILA[2] and Ana MOURA[3]

[1]*Department of Economics, Management, Industrial Engineering and Tourism, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, E-mail: marianafribeiro@ua.pt*

[2]*Research Unit on Governance, Competitiveness and Public Policies, Department of Economics, Management, Industrial Engineering and Tourism, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, E-mail: liliana.avila@ua.pt*

[3]*Research Unit on Governance, Competitiveness and Public Policies, Department of Economics, Management, Industrial Engineering and Tourism, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, E-mail: ana.moura@ua.pt*

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***ABSTRACT**: This paper presents a case study of a manufacturing company that faced challenges due to the absence of a systematic method for defining the routes of Mizusumashi operators responsible for supplying assembly cells. Fluctuating production levels and a manual route planning process resulted in imbalanced workloads for the operators, leading to supply failures and idle time. To address this issue, an algorithm was developed to implement an Integer Linear Programming model for the Vehicle Routing Problem. This model considered various constraints, including the maximum time allowed for each route, the number of vehicles and their capacities, as well as visit precedencies and service times at each location. The primary goal was to create a tool that could adjust routes in real-time according to the significant variability in demand while minimizing total travel time. The algorithm was successfully implemented, leading to a reduction in time spent on logistical tasks, improved resource allocation, enhanced decision-making capabilities, and greater operational agility.*

***KEYWORDS**: Mixed-integer linear programming, Vehicle routing problem, Heuristic-based approach, Internal logistics*

1 INTRODUCTION

In today's highly competitive business environment, organizations must gain a comprehensive understanding of their internal operations and adopt innovative strategies to reduce operational costs effectively. Within manufacturing companies, internal logistics is pivotal for managing the seamless flow of materials throughout the production process (Goldsby & García-Dastugue, 2003), significantly influencing the overall performance of assembly lines (Alnahhal et al., 2014).

Unfortunately, many organizations overlook essential internal logistics activities, often viewing them as non-value-adding elements that do not directly contribute to the final product. This focus on customer-perceived value can lead to inefficient processes that hinder productivity. However, improving internal logistics is crucial for enhancing operational efficiency and boosting overall productivity (Issa, Dašić, & Todorov, J., 2022).

Internal logistics managers must consider various supply and demand dynamics to effectively manage these logistics. They need to accurately predict crucial factors, including the type and quantity of materials required, the responsible parties for handling these materials, the optimal locations for storage and transportation, the timing for transporting goods, and the methodologies for executing these logistics tasks (Kluska & Pawlewski, 2018). By refining these processes, companies can achieve better resource utilization, reduce waste, and improve their competitive edge in the marketplace.

Several logistics solutions can be implemented to ensure that efficient materials are supplied within factories. One such solution is the Mizusumashi system. This system operates as a cyclical collection and supply mechanism that utilizes standardized routes. Its main objective is to deliver the required materials in the right quantity, at the right time, and to the designated location, ensuring continuous production flow (Nomura & Takakuwa 2006).

This paper reports on the case of a manufacturing company facing some challenges related to Mizusumashi route planning. The process has been done manually and, therefore, not optimized. Moreover, fluctuations in production levels put pressure on the system and cause imbalances in operator workloads, leading to supply failures and idle time. The company needed a tool to optimize routes and redefine them whenever necessary, considering changes in supply needs.

The problem presented was tackled as a Vehicle Routing Problem (VRP) aimed at designing the least-cost delivery routes from a depot to a set of geographically sparse customers subject to side constraints (Laporte, 2009). Given the significant variety of side constraints and optimization goals that can be considered, resulting from the diverse rules and constraints encountered in real-life applications, there are several works that deal with internal logistic routing applications, such as Braekers, Ramaekers, & Van Nieuwenhuyse (2016), Mehami, et al. (2018), Fabri et al. (2019), Romeira & Moura (2023) and Fabri & Ramalhinho (2023). In the case under study, the most important constraint concerns the visit precedencies that must be considered for each assembly cell.

After identifying the main problem constraints, data was collected, including travel times between stopping points and the service time of each stopping point. Then, with the mathematical model finalized, an algorithm was developed to allow data preprocessing, thus reducing computational time, and the dynamic reconfiguration of routes, providing flexibility to adapt to production fluctuations. Finally, a graphical interface was created to facilitate the use of the tool. The algorithm was validated by comparing the cycle times measured on the shop floor with those obtained through the developed algorithm.

The reported case study can guide other organizations facing similar challenges, providing important insights into operationalizing a solution to optimize the route planning process, especially in contexts where production levels fluctuate.

2 PROBLEM DESCRIPTION AND MOTIVATION

The company under analysis specializes in bathroom solutions, with a strong focus on producing flush cisterns. The assembly sector constitutes a substantial part of the factory (Figure 1), organized into seven distinct areas, with assembly cells operating in three shifts. In this sector, components manufactured in-house or purchased from external suppliers are assembled to create intermediate and final products.

A set of Mizusumashi carries out the process of supplying the assembly cells. The Mizusumashi operators collect the components in supermarkets and supply mostly assembly cells. In addition to transporting and supplying materials to the assembly cells, the operators are also responsible for collecting, transporting, and supplying cardboard used to pack the final product. The cardboard must be picked up at different supermarkets that are exclusive to cardboard. Sometimes, it is also necessary to supply the assembly cells and some production cells composed of semi-automatic machines.

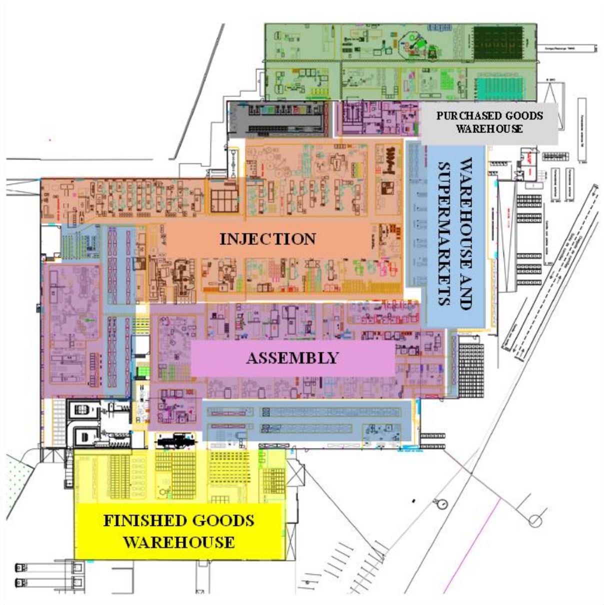

Fig. 1 Factory layout

There are several Mizusumashi, each with a fixed route and a defined number of points/workstations to supply. Existing routes were developed based on the experience and knowledge of employees. However, in the last years, the company has faced high fluctuations in production levels, leading to consequent overload or underload for the operators executing the routes. During an underload period, operators might have only one station to supply and a long period of inactivity. In this case, the time was spent organizing the supermarkets or assisting other operators. On the other hand, during an overload period, a greater stress environment was observed among the operators, who were trying to meet their goal of avoiding supply disruptions at the workstations. Analyzing data from 2023, a correlation was observed between overload periods and an increase in supply disruptions and non-conformities.

The internal logistics manager intervened in such situations, attempting to readjust and recalculate the necessary routes based on their knowledge and experience without using any other method or technology. Besides the time spent making these adjustments, the procedure did not ensure the efficiency of the supply process.

Although functional, it lacked a more efficient, systematic approach adapted to the factory's dynamic needs. Therefore, creating a user-friendly tool was proposed, which would not only improve the existing routes but also allow for their rapid reconfiguration in response to variations in production levels. Dynamic routes will enable a quick response, helping to meet changing supply needs while optimizing the process, reducing downtime, and increasing efficiency.

3 AN HEURISTIC-BASED APPROACH

A comprehensive hybrid strategy was developed to seamlessly integrate a sophisticated mixed-integer linear programming model specifically designed to tackle the complexities of the Vehicle Routing Problem (VRP). Coupled with this model is an advanced algorithm that enables efficient data preprocessing, thereby streamlining the overall process. This approach not only simplifies the intricacies of the model but also significantly reduces computational time, enhancing the effectiveness and efficiency of the routing solutions.

3.1 Constraints and Data Collection

Firstly, the requirements and constraints of the problem at hand were defined. Those constraints and requirements are needed to ensure a correct and efficient supply of the manufacturing cells:

- Each route is to have a maximum duration of 40 minutes, in line with the company's established standards for existing routes. However, this duration will be a configurable parameter within the algorithm, enabling decision-makers to adjust it as needed to accommodate future changes in route duration.
- Every manufacturing cell designated for supply must have a specified service time. This service time represents the total duration required to efficiently unload materials from and load them back into the Mizusumashi. It encompasses all steps involved in the process, ensuring that each cell is fully equipped and prepared for optimal operation.
- The factory has a finite quantity of Mizusumashi, which imposes constraints on the number of routes that can be generated. This limitation should be incorporated as a parameter in the algorithm.
- Every Mizusumashi has a maximum capacity dictated by the finite number of wagons it can couple with. Each wagon is designated to store materials for a single manufacturing cell, thereby limiting the number of cells that each Mizusumashi can serve. This will also be a parameter considered in the algorithm.
- The sequence of visits is crucial to consider, as the Mizusumashi must go through one or more supermarkets to gather the necessary materials for effectively supplying a designated manufacturing cell. So, it will be necessary to consider precedence constraints between some of the visit points. By prioritizing the order of these visits, the Mizusumashi can optimize their workflow and ensure that all required supplies are collected promptly.
- Another important consideration involves the various crossings that need to be carefully assessed when planning a route through a narrow aisle in a factory setting. Proper evaluation of these crossings ensures that the route maintains safety and efficiency, preventing potential collisions and allowing for smooth movement of personnel and materials.

Considering all these parameters and constraints, a precedence list was drawn up for each manufacturing cell, and a service time for each stop point was calculated. A mapping of all tasks involved in the material supply process to the assembly cells was carried out, as well as a time study to determine the duration of each task. Table 1 shows the duration of the most relevant tasks.

Table 1. Duration of the most important tasks performed by Mizusumashi operators

Task	Duration (sec.)
Collecting a box in the supermarket	4
Handling cardboard in the supermarket	7
Supplying a box to the assembly cell	4
Collecting a box with the finished product in the assembly cell	7
Handling EPS	113
Handling cardboard to supply an assembly cell	13
Coupling/decoupling a wagon	15
Leaving an empty box in the warehouse	4
Placing waste in the cage	8

They include handling (collecting or supplying) boxes, collecting empty boxes, transporting finished products from the cell to the pallet, and providing cardboard for packing. The time required for supplying EPS (Expanded Polystyrene) and coupling/decoupling the wagon was also estimated because the Mizusumashi cannot directly access some assembly cells. Additionally, the feeding times for semi-automatic machines in certain cells were measured, as it is another task performed by Mizusumashi operators.

The number of boxes handled per cycle may vary depending on whether it is a setup or a regular operation. A setup requires Mizusumashi to supply more boxes initially to ensure all the materials needed to begin production. If the supply is done later, with the production running, the 'full box/empty box' rule is followed from cycle to cycle. Therefore, this was considered when calculating the total service time. An Excel file was created to facilitate the calculation of service times for each assembly cell, allowing these values to be easily updated whenever necessary. Data on the production order history, bills of materials, cycle times and box capacity are imported from the Enterprise Resource Planning (ERP) system to estimate the number of boxes to be handled, providing a service time more accurately aligned with reality.

Moreover, a matrix of travel times between all stop points was developed. Distances between all stopping points were collected, and the average speed of a Mizusumashi was calculated to determine the travel time between each pair of stopping points. The distance matrix was created based on the existing factory layout with coordinates and using the QGIS software. The speed of the Mizusumashi was calculated by dividing the length of existing routes by its travel time, resulting in an average speed of 1.17 m/s. This average speed was considered when calculating the travel time between each pair of stop points.

3.2 Mathematical model

A mixed-integer linear programming model was defined once the data was processed and the problem constraints were identified.

The VRP, is defined over a directed graph *G (P, A)* where *P = {1, ..., n}* is the set of stopping points and *A = {(i,j):i,j ϵ P, i ≠ j}* the set of direct connections between them. The length of each arc, d_{ij}, corresponds to the distance between i and j, and t_{ij} the travel time between the two points.

Two decision variables were defined:

- $x_{ij} = \begin{cases} 1, \text{if the edge } (i,j) \text{ is used} \\ 0, \text{if not} \end{cases}$;
- u_{ij}, integer variable that represents the position of node i in the route to avoid subroutes.

The mathematical formulation is given in (1)-(4), where the objective function (1) minimizes the total travel time of the routes. Constraints (2) and (3) ensure that each stopping point is only visited once. Constraint (4) ensures that no subroutes are formed within the main route by excluding the starting point.

Minimize $Min \sum_{i=0}^{n} \sum_{j=0}^{n} (t_{ij} \times x_{ij})$ (1)

Subject to:

$\sum_{j=1, j \neq i}^{n} x_{ij} = 1, \forall i \neq 1 \in P$ (2)

$\sum_{j=1, j \neq i}^{n} x_{ij} = 1, \forall i \neq 1 \in P$ (3)

$u_i - u_j + |P| \times x_{ij} \leq |I| - 1, \forall i, j \in \text{P}, \text{i} \neq \text{j}, \text{i} \neq 0, \text{j} \neq 0$ (4)

The constraints delineating the maximum cycle time for routes and the capacity limit on the number of wagons attached to the Mizusumashi were intentionally excluded from the mathematical model. Instead, these parameters will be addressed algorithmically to minimize computational complexity and enhance methodological flexibility. The mathematical model retains consistency and adaptability across various scenarios, permitting the inclusion or exclusion of additional constraints without altering its foundational structure. This characteristic is essential, as the organization seeks to derive two distinct sets of results: one incorporating the maximum cycle time constraint and the other excluding it. Consequently, this approach enables a comprehensive analysis of different scenarios, facilitating strategic decision-making grounded in tailored information that aligns with actual operational requirements.

3.3 The hybrid approach

An algorithm was developed in Python to support the implementation of the mathematical model. The algorithm addressed one of the most challenging aspects of the problem: ensuring that assembly cells are visited and supplied only after one or more supermarkets have been visited to collect the materials for supply (i.e. visit precedence). The algorithm allows data preprocessing before allocating assembly cells to routes, ensuring that corresponding supermarkets are always included in the routes.

The algorithm (see Figure 2) is initiated once the user provides all the necessary input parameters: the active assembly cells, the number of available Mizusumashi, the maximum route duration, and the

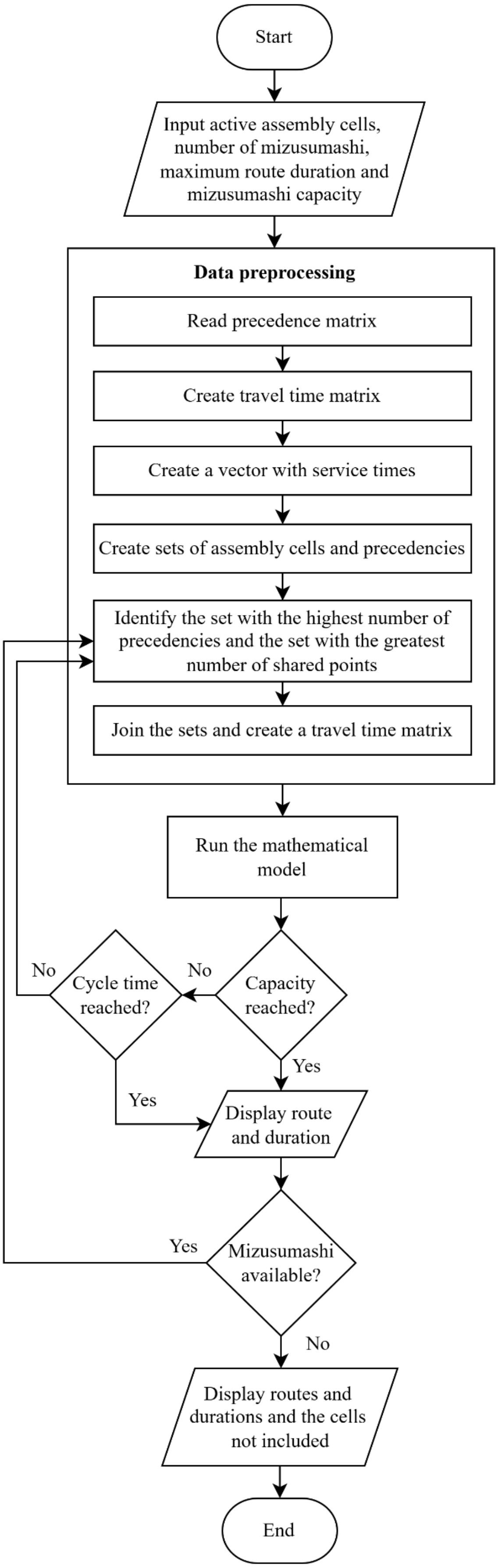

Fig. 2 Algorithm developed

capacity of each Mizusumashi. After these inputs are entered, data preprocessing tasks begin. These tasks include reading the precedencies of each active assembly cell, constructing a travel time matrix for the active cells along with their corresponding precedencies, and creating a vector that outlines the service time for each stop point.

Multiple sets are generated, each containing an assembly cell and its corresponding precedencies. The set with the highest number of visit precedencies is identified as the starting point and is then assigned to the first Mizusumashi.

The algorithm iterates through all the remaining sets to identify the one with the most common stopping points. It is assumed that having a greater number of common points will result in a shorter travel distance for the Mizusumashi. Conversely, if the two sets share no common stopping points, the travel distance will likely be longer. However, alternative criteria and strategies could be applied to select the initial set and to combine sets in a way that may also yield a good solution.

Once the optimal set is selected, it is merged with the initial set. To minimize computational time, a travel time matrix is constructed using only the stopping points from the newly merged set, which includes the two assembly cells and their visiting precedencies. This completes the data preprocessing phase. The next step involves solving the mixed-integer linear programming mathematical model to determine the optimal route while considering the selected points.

Upon obtaining the optimal solution for the Mizusumashi route utilizing the two merged sets, the subsequent step involves verifying that the problem constraints are satisfied. The route must comply with the maximum capacity established by the user (specifically, the M capacity should exceed the number of merged sets) and adhere to the maximum allowable route duration. When these conditions are met, the process is repeated.

A new set, comprising an assembly cell and its corresponding precedencies, is added to the merged set, resulting in three merged sets. The algorithm then generates a new solution for the Mizusumashi route based on this updated merged set. If either the Mizusumashi capacity or the maximum route duration is exceeded, and Mizusumashi are still available to create new routes, the process restarts with a new set drawn from the remaining available ones that have not yet been included in any previously obtained routes. This cycle continues until all constraints are fulfilled.

Ultimately, the algorithm displays all the routes obtained and their respective durations. It also highlights any assembly cells that remain unallocated to any route, if applicable. Furthermore, a graphical interface has been developed to assist users in determining routes for Mizusumashi using the algorithm.

4 HEURISTIC-BASED APPROACH VALIDATION

To evaluate the algorithm's effectiveness in accurately replicating real working conditions and to determine the reliability of the results concerning the cycle time of the Mizusumashi routes, we collected time data from various Mizusumashi routes on the shop floor during all three operators' shifts. We then compared these collected times with those obtained using the Mizusumashi route sizing application (Table 2). We calculated the Absolute Percentage Error (APE) to assess the variations in cycle time values. This metric is particularly beneficial when the primary focus is on the magnitude of the error whether positive or negative.

The company has implemented an acceptance limit of 10% for the Average Process Efficiency (APE), carefully considering the various unforeseen challenges in the logistics process. Such challenges include fluctuations in the distribution of tasks among assembly cells and variations in the speed at which operators complete their assignments—factors that are often beyond full control.

Table 2. Comparison of the cycle times of the routes monitored on the shop floor and those obtained through the developed algorithm

Route	Shop floor	Algorithm	Absolute percentage error (%)
R1	26m 41s	27m	1.2
R2	39m 33s	37m	6.4
R3	45m 32s	46m	1
R4	30m 22s	30m	1.2
R5	42m 02s	41m	2.5
R6	29m 38s	29m	2.14
R7	58m 32s	60m	2.5

To optimize workflow, the assembly cells are thoughtfully designed with ample space, allowing for the accommodation of materials from two complete Mizusumashi rounds, as well as an additional bin to provide extra capacity when needed. This strategic setup promotes smoother workflow and enhances the system's flexibility in responding to unexpected disruptions. As a result, operations at the assembly cells can continue with minimal interruptions, even when there are discrepancies between the estimated and actual durations of the logistics routes.

Remarkably, the results consistently fall within the acceptable limit of 10%, validating the robustness and reliability of the algorithm that has been developed. This success reflects the company's commitment to efficiency and adept handling of the inherent complexities within the logistics landscape.

5 CONCLUSION

This paper discusses the development of an algorithm designed to redefine Mizusumashi routes in real-time, allowing for quick adjustments based on fluctuations in production levels.

The implementation of this algorithm in the manufacturing company under study has demonstrated numerous advantages over the previous manual route planning process. The logistics manager can now obtain optimized Mizusumashi routes quickly and accurately, leveraging reliable data rather than relying solely on intuition for decision-making. Furthermore, the capacity to swiftly respond to changes in production needs—without extensive manual calculations—enhances the agility of logistics operations. This reduces the time spent on route planning and allows the logistics manager to concentrate on other value-added activities, thereby improving resource management efficiency and mitigating the risks of operator overload or underload.

However, the data needs to be regularly reviewed and updated to ensure that the solutions provided align with the company’s operational realities and remain relevant. The developed tool is adaptable to changes within the company, allowing for updates to service times and the number and capacity of the available Mizusumashi, without requiring alterations to the algorithm's formulation. Nonetheless, there is room for improvement, such as adding features allowing users to select the maximum duration for each route or considering Mizusumashi with varying capacities.

The case study presented in this paper offers valuable insights to other companies facing similar challenges. It can assist them in identifying key restrictions to consider in similar scenarios and the necessary data to be collected and analyzed, thereby providing important guidance on how to optimize the route planning process effectively.

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