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AMR in intralogistics: influence of the operating environment and comparison with traditional transport vehicle

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Abstract

With the advent of Industry 4.0, new technologies were born and then introduced into industrial environments to support logistics systems. Logistics 4.0 consists of wireless sensor networks, internet of things, automated guided vehicles, 3D printing, drones, cloud computing, blockchain, big data, robotics and automation and augmented reality (Tubis & Poturaj, 2021). Among these, self-driving vehicles have evolved, allowing any type of load unit to be transported and any area of the industrial environment to be reached. A particular class of AGV called autonomous mobile robot (AMR) has become increasingly popular in companies to carry out intralogistics operations thanks to their flexibility to adapt to the industrial environment, the ability to make autonomous decisions, to avoid obstacles along the way and to optimize the path to reach their goal. However, there are many challenges that these vehicles must overcome to operate efficiently in a dynamic and interactive environment such as the intralogistics one. The intralogistics environment includes both storage points such as the warehouse and the production environment where materials are transported to supply stations and assembly lines. Operators, loading units (luC), transport systems and materials are part of the intralogistics system.

The first objective of this thesis is therefore to find which characteristics of the intralogistics industrial environment influence the functioning of AMR. To this end, a qualitative methodology was used based on an analysis of the literature and on observations made during a visit to a manufacturing company operating in Sweden. At this point it was possible to build a theoretical framework to organize information on AMRs within the intralogistics industrial environment and answer the first research question. The theoretical framework involves an exploration of the part feeding problem (PFP), i.e. the problem of supplying parts to assembly lines and stations in the intralogistics field and then identifying the critical issues of this environment on AMR components . PFP is divided into storage, transport and feeding policy. The part relating to the transport system represents the main part in which the means of transport and in particular the AMRs are described. The AMR was divided into its software and hardware components from which it was possible at a qualitative level to identify which characteristics of the industrial environment influenced the performance of the AMR. These are layout complexity, unit load, human and vehicle interaction, network connection and floor and atmospheric conditions. To conclude and answer the first research question, each factor of the intralogistics industrial environment that influences the performance of the AMR, found by the analysis, was traced back to each component of the AMR (both software and hardware).

The second objective of this thesis is to answer the second research question and therefore compare AMRs with traditional vehicles in terms of performance. To this end, a quantitative approach was used in which simulation software was used to analyze an industrial case. The Swedish company provided data on the flow of materials and the location of the loading and unloading stations. First, an analysis was performed on the transport order data on Minitab to identify the statistical distribution that best approximates the data for each station to be served by the vehicle (AMR or forklift). At this point the construction of the simulation scenario followed. The simulation scenario in Flexsim allows us to simulate the behavior of stations or machines using processors while the means of transport is represented by a task executer (AMR or forklift in our case). Within the first simulation scenario, the performance of the AMR is tested by measuring KPIs. The KPIs were selected both to test the performance of the AMR and that of the machines. Idle time, loading, unloading, travel empty and travel loaded are the KPIs used to measure the performance of the AMR while waiting for transport and processing are the parameters used for the machines. The results of the first scenario are shown for different flow rates, reducing the transport request deltas between one order and the next. From the results of the AMR KPIs of these scenarios it is found that the AMR manages to satisfy all transport requests during the work shift and that the Idle time decreases as the capacity of the machines increases. From the analysis of the KPIs of the processors, however, we find that the machines are served well by the AMR. In particular, the high processing state and the relative low waiting for transport data allows us to conclude that, for the real scenario and the analyzed data, an AMR is more than sufficient to satisfy the transport requests. The forklift scenario is simulated by varying the vehicle parameters and loading and unloading times. The results compared with those of the AMR lead us to conclude that the forklift is sufficient to satisfy the transport requests of the shift but is slower than the AMR in carrying out the tasks, therefore, there is a higher loading and unloading time and a reduction of idle time. To conclude and answer the second research question, in terms of performance and with the relevant hypotheses, the AMR is more advantageous than the operator-driven forklift.

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1 INTRODUCTION

To provide a better understanding of the problem addressed by this thesis and how the work was carried out, the introductory chapter is divided into the following parts: background, problem statement, aim, delimitations, and thesis outline.

1.1 Backgound

Materials handling is an integral part of the materials flow in the logistic systems, comprising the activities related to physical materials supplying in an organization. According to Jankuloska et al. (2019), the activity related to material handling are: predicting the needs for materials, determining the material sources, the materials delivery into the organization and monitoring the state of the materials as current assets.

This research specifically focuses on the activity of transporting materials within internal logistics, supporting production in manufacturing companies. Material transportation does not have a direct connection with consumers; however, the availability of raw materials, materials, and semi-finished products for production directly influences the availability of finished products for consumers. Decisions made at this stage of the logistics system have a direct impact on the quality of services offered to customers, affecting the company's competitiveness and the profits generated in the market (Jankuloska et al. 2019). If the management of the internal flow of materials is not efficient and effective, production cannot provide products at the price and within the time desired by consumers. Therefore, it is essential for logistics system managers to fully understand the role of material handling and how it affects production costs on one hand, and customer service on the other. Frequently, due to inadequate material management, issues such as waste, losses due to damage, irregular flows, excessive movements, wasted warehouse space or oversized warehouses, a high number of employees, lack of parts or suppliers, and so on, can arise (Jankuloska et al. 2019).

System and process of material movement are used to enhance customer service, decrease inventory, shorten shipping times and decrease general production, distribution and transportation expenses (Orestis et al. 2019). Is it therefore evident the importance of having effective and efficient materials supply and management systems for production. The material handling process includes a wide range of manual, semi-automated and automated transport and systems supporting logistics and making the supply chain work. Among these, the most flexible automatic transport systems are represented by autonomous guided vehicles (AGVs). AGVs are autonomous material handling systems, meaning they do not require operator intervention. They are used by manufacturing industries primarily in internal logistics for moving materials within production departments and warehouses. These systems are not new; in fact, their first application dates back to the USA in the early 1950s (Ulrich, 2015). These systems have evolved over the years, and according to Ulrich (2015), we can divide the evolution of AGVs into three past eras:

- The first AGVs epoch:
  Technologically, the first systems were characterized by the simplest track guidance techniques and tactile sensors, such as bumpers or emergency stop bars for workers' protection and safety, with mechanical switches. From the mid 1960s onwards, the first individual transport applications and transport as part of the "linking" of workstations were found, and the first systems were used in order picking in the food industry. The variety of vehicles was limited to tractors, forklift trucks and platform trucks.
- The second AGVs epoch:
  The second epoch lasted through the 1970s and 1980s and ended in the early 1990s. The electronics arrived in the form of simple on-board computers and large control cabinets for the block section control of the plant. In the 1970s , the typical AGV was finally created. As production efficiency increased and manually operated transport systems were used, the demand for a higher degree of automation developed, which should reduce production costs in the long term. In this era, AGVs began to be used as transport vehicles to support production, particularly tractors, piggyback, and forklift truck AGVs for assembly supply, in the warehouse, for picking and material delivery to the lines, and taxi operation in intralogistic applications. However, the flexibility of these systems was not optimal, and small changes in the vehicle's route were very costly. Moreover, the overall market volume was too small, and a specific supplier market did not develop to provide the necessary components and support for the implementation of these systems, which were secondary to traditional operator-driven transport systems. Therefore, AGVs were used only by large manufacturers, particularly in the automotive sector.

- The third AGVs epoch
  The third epoch, which lasted from the mid-1990s until around 2010, was characterized by the creation of technological standards and market consolidation. The vehicles were equipped with electronic controls and contactless sensors. A standard PC was used as the main control system for the AGVs, while a PLC or microcomputer was present on board the vehicle. In this era, AGV systems became reliable because manufacturers now had various proven technologies to choose from and design new systems. Additionally, technological advancements also led to improvements in production methods, storage, material flow, and

assembly techniques, supporting the implementation of AGVs in internal logistics. The so-called flexible manufacturing systems (FMS) are born. According to Vlachos et al. (2022), a FMS is an integrated, computer-controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium-sized volumes of a variety of part types. In the field of internal logistics, within FMS, AGVs can now move any type of load unit such as pallets, boxes, bins, etc., reach any area of the production system and the warehouse, and position the load unit precisely and ergonomically for the operator. In conclusion, it can be stated that this era has led to an increase in the use of AGVs by industries that have successfully employed these vehicles to optimize material transportation.

Today, we are living the fourth epoch of AGV development (Ulrich, 2015), which is driven by Industry 4.0. The concept of Industry 4.0, first introduced at the Hannover Fair in 2011, focuses on the Fourth Industrial Revolution, aiming to enhance operational efficiency and productivity through increased automation. Key features include digitalization, optimization, and customization of production, automatic data and communication sharing, advanced human-machine interaction, automation and adaptation, as well as additional value-added services (Orestis et al., 2019). Indeed, what emerges from the previous description is the realization of the "smart factory." These facilities have the ability to adapt quickly to changes to achieve business goals, optimizing resource usage, and acting autonomously, without requiring human intervention. Furthermore, with the rising of Industry 4.0 we are witnessing a paradigm shift from centralized, hierarchical organization principles and towards dynamic, networked, autonomous systems that cooperate with each other and are optimized in themselves in dynamically changing environment. This change is also reflected in intralogistics systems and processes. Intralogistics process, according to Fottner et al. (2020), regardless a complex interplay of different logistics functions covers the organization, control, execution and optimization of internal material and information flows. Therefore an autonomous intralogistics system is a systems enable self-contained, decentralized planning, execution, control, and optimization of internal material and information flows through cooperation and interaction with other systems and with humans (Fottner et al. 2020). Figure 1.1 represents the ongoing change between conventional intralogistics systems and autonomous intralogistics processes.

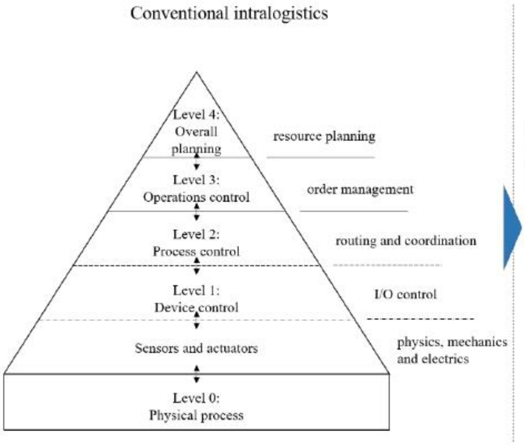


Figure 1.1: Transition between conventional intralogistics systems and autonomous intralogistics systems (Fottner et al. 2020)

The paradigm shift from centralized to decentralized systems and the widespread adoption of Industry 4.0 has led to the emergence of Logistics 4.0. The key element of Logistic 4.0 concept is the creation of a cyberphysical system supporting logistic processes (Tubis & Poturaj, 2021). The term cyber-physical systems (CPS) refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. According to Barreto et al. (2017) Logistics 4.0 can be seen as a supply network where all processes can communicate with each other, as well as with humans for enhancing their analytical potentialities throughout the supply chain. The most important technology used in Logistic 4.0 are shown in figure 1.2

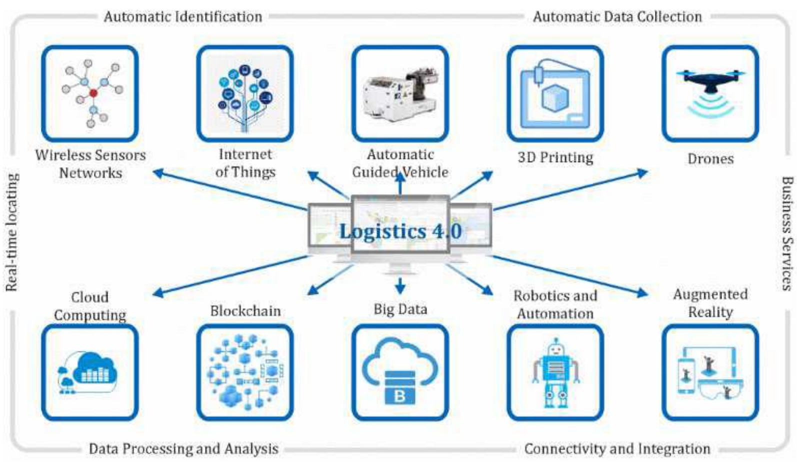


Figure 1.2: Components and technology of Logistics 4.0 (Tubis & Poturaj, 2021)

In this context, AGVs have evolved with new technologies that have allowed them to be equipped with cutting-edge sensors and control systems, enabling them to autonomously identify themselves, determine their present location and collect data on their status and the products being transported (Ortesis et al. 2019). These AGVs represent a new class of autonomous vehicles known as autonomous mobile robots (AMRs). In comparison between AGVs, the AMRs in industrial settings employ a decentralized decision-making approach to navigate without collisions, offering a platform for tasks such as material handling, collaborative activities, and comprehensive services within a defined area (Pizoń et al. 2024). AMRs do not move along a fixed path, as is the case with AGVs, but rather move to any accessible and collision-free point within a given area. Furthermore, small changes due to, for example, a machine layout change would typically take substantial time for most AGV guidance systems, cause periods of inactivity, and risk economic losses and decreases in productivity. AMRs, however, can adapt quickly to changes in the operating environment (Frangapane at el. 2021). The focus of this research is on the use of AMRs in material transportation within the internal logistics of manufacturing companies. The benefits that these vehicles can bring to the improvement of the material transportation process to the lines are numerous, including reduced labor costs, excellent safety, accuracy, and productivity (Tubis & Poturaj, 2022; Correira et al., 2020). Compared to traditional material transportation systems (such as forklifts, pallet jacks, and conveyors), according to Tubis & Poturaj (2022), Correira et al. (2020), Golova et al. (2021), and Ulrich (2015), they are advantageous because:

- They ensure a safer working environment through the use of safety sensors that intervene by stopping the vehicle in the presence of an obstacle (operator or any other obstruction in the vehicle's path). This also guarantees a reduction in indirect costs due to increased safety and a decrease in accidents.
- They can operate 24/7 with minimal labor and human intervention costs.
- They can transport any type of load unit and even multiple units if multi-load AGVs are used.
- By optimizing transport routes and minimizing empty trips between material storage and production points, it is possible to reduce material delivery time and distance traveled. Thanks to the reduction in distances and delivery times, the energy consumption of these vehicles is also optimized.
- They offer a more flexible solution, resulting in more efficient material transportation because they can dynamically adapt to production changes due to market demand variability.

The benefits of using AGVs for material transportation are interesting; however, in addition to the issue of introducing these vehicles, which is not immediate, several challenges must be addressed by companies when working with AGVs, as will be seen in the next section.

1.2 Problem Statement

Nowadays, production systems must cope with the emerging trend of mass customization, which introduces challenges such as frequent product changes and lower demands for individual products (Adenipekun et al., 2021). The increasing complexity in production and internal logistics is also due to factors such as the globalization of business, dynamic and volatile markets, and shorter product life cycles (Fottner et al., 2021). Manufacturing assembly systems are particularly affected by the effect of mass customization of products because there is an increasing number of different parts to manage. The problem of high product variety has been mitigated in manufacturing industries through the use of mixed-model assembly lines (MMALs), which have become increasingly prevalent in assembly systems (Müllerklein et al., 2022). They allow the production of different products on the same line without any restrictions on the production sequence. The performance of assembly lines depends on the availability of parts and subassemblies that constitute the final product and must be delivered to the lines at the minimum cost (Battini et al., 2015). In this intricate setting, an assembly-to-order (ATO) manufacturer recognizes the necessity of storing a portion of inventory within the facility to maintain efficient operation of production systems and assembly lines, as well as to accommodate fluctuations in market demand (Battini et al., 2015). Apart from storing assembly components and managing inventory, there is a need to determine the most efficient method for supplying these items to the appropriate assembly line at the correct position and within the designated time window. This challenge is known as the part-feeding problem (PFP). In accordance with Battini et al. (2015), the PFP cannot be resolved without making appropriate decisions regarding the choice of component storage type, the selection of transport means, and the determination of the feeding policy, i.e., how components are presented and managed for delivery to the lines. In this context, the role of the transport means is to deliver materials from the storage area to the assembly lines. In practice, this type of transportation does not necessarily have to be carried out with a single type of vehicle, but various solutions are available for delivering materials to the lines (Ulrich, 2015; Adenipekun et al., 2021). Among the types of transport vehicles used in this context, two main categories can be identified (Pareschi et al., 2011): traditional transport systems (such as forklifts) and AGV systems.

The problems that this research wants to investigate concern on the one hand the characteristics that make these vehicles advantageous compared to traditional means of transport in the PFP and on the other the influence of the operating environment on the functioning of the AMR. In fact, one problem that the literature analysis does not extensively discuss concerns the characteristics of the production environment in which these vehicles must operate. AMRs must interact with operators, as well as with other vehicles (such as other AGVs or traditional transport systems), move along corridors between stations, traverse different areas of the production system, avoid obstacles along the path and so on. All these interactions with the vehicle can pose limitations to the functioning of AMRs in production systems and may lead to production stoppages due to material shortages at the lines.

1.3 Purpose of the Research

The background and problem statement highlight the context and the issue of material transportation in internal logistics that companies face today to maintain production systems at a certain level of efficiency. In this section, the aim is to emphasize the contribution of this thesis by defining research questions to which answers were sought.

The purpose of the research is to compare the choice of transportation means for materials in intralogistics between traditional transport vehicles and automated vehicles. The thesis focuses on the role of transportation within the PFP, particularly the use of automated guided vehicle. Among automated vehicles, the primary focus will be on AMRs. The comparison between the two material transport systems will be carried out by considering the effect of the production environment on the AMR operation and a simulation software to test the performance of the system.

To reach the purpose of the thesis, research questions have been formulated, to which answers will be sought. The first research question was posed to investigate the characteristics of the production environment that facilitate the operation of AMRs and whether these are conducive to the integration of these vehicles for material transport. Therefore, the first research question is:

RQ1: *What are the characteristics of the production environment that impact the operation of AMRs? Are these characteristics a prerequisite for the operation of AMRs?*

The second research question, instead, aims to investigate the advantages, in terms of efficiency of material transport, in the used of AMRs in the PFP compare to traditional transport system. Therefore, the second research question is:

RQ2: *What are the advantages, in terms of performance of the transport system, of using AMRs for material transport compared to traditional transport systems ?*

1.4 Delimitations

In this section, some considerations will be made on the limitations of the research thesis. As regards the industrial environment analysis, this is limited to the intralogistics manufacturing one. In general, we can say that the system is made up of different techniques for managing materials for assembly (kitting, line stocking) as will be described in chapter 3. There is also a central warehouse where vehicles collect the material to be transported to the lines and smaller decentralized warehouses positioned within the production department (supermarket). Production is organized in workshops where the production machines are grouped according to the Group Technology concept. The assembly lines are placed in dedicated areas between production and the material storage points and different means of transport (traditional vehicles and automated vehicles) are used to supply the lines. The comparison between AMR and traditional vehicles is carried out considering the ideal machines, therefore without setup times and failures. Furthermore, the comparison is carried out by analyzing the case study of a Swedish company in which the data provided are related to low-frequency transport orders in which pallets are moved. The transport capacity is one load unit (1 pallet at a time is moved) and the vehicle used up to now for pallet movement is the forklift which will therefore be used as a traditional vehicle in the simulation for comparison with the AMR. The technical data on the AMR specifications were provided by the company and are related to an AMR forklift model. The results obtained to answer the second research question are valid only if the hypotheses of the case in question are made, i.e. ideal machines (without set-up times and failures) and with the technical specifications (speed, acceleration, deceleration and load capacity) introduced in chapter 4 of the case study. Furthermore, the comparison is carried out by customizing the simulation to the intralogistics environment of the company maintaining real distances and the positions of the loading and unloading stations according to the layout of the CAD file provided.

1.5 Thesis Outline

After the introduction, the methodology chapter will be presented, detailing how the work was organized and the information and data necessary to answer the research questions. Qualitative analysis will be used to organize information from the literature and subsequently to draft the theoretical framework. The theoretical chapter aims to describe in general the sub-problems that constitute the PFP, particularly focusing on the choice of AGVs as a means of transport. The main focus will be on AMRs. Quantitative analysis will be used to analyze data from a Swedish company that utilizes various types of material transport and is in the process of introducing two new AMRs into their internal transport system. The analysis considers the number of AMRs employed, the plant size, the plant layout, and the transport flow between different stations to compare AMRs and traditional transport systems. The comparison will be conducted using simulation software, Flexsim®. The conclusions will discuss the results obtained to answer the research questions.

2. METHODOLOGY

The goal of this chapter is to describe the methodology employed to answer the research questions and thus achieve the objective of the thesis. The information provided in this chapter is based on a strategy for properly organizing information and data.

2.1 Research strategy

The research strategy is used in this case to provide and describe the methods employed to address the research questions. There are two major approaches to research that can be used in the study of the social and the individual world. These are quantitative and qualitative research (Yilmaz, 2013). The research strategy for this project involves a comprehensive approach that used both qualitative and quantitative methods to investigate the use of AMR in intralogistics for material transportation. The methodology is structured into two primary sections: a qualitative and a quantitative analysis. This dual approach ensures a thorough examination of the topic, combining theoretical insights with practical, data-driven evaluations.

2.1.1 Qualitative

Qualitative analysis is used to analyze data that cannot be measured and interpreted statistically. There are different methodologies for conducting a qualitative analysis, for example interviews or focus groups. In this research the qualitative analysis is based on the collection of information through the review of the literature and the observations coming from the visit to the company. In the next section, dedicated to qualitative analysis, it will be explained how this information was collected and organized.

2.1.1.1 Literature review and observation from company visit based qualitative analysis

The qualitative component of this research focuses on a comprehensive literature review and observation from company visit to establish a theoretical framework and identify which aspect of the industrial environment could affect the operation of the AMR in the part feeding. The qualitative analysis was therefore used to answer to the first research question (RQ1). The steps involved in the qualitative method include:

a. *Literature review*: A review of existing academic and industry literature was conducted. The search for documents was carried out through Google Scholar. The documents includes journal articles, conference papers, case studies, and industry reports related to AGVs, AMRs, and material transport systems in in-bound logistics. Initially, the selected articles were chosen to holistically understand the problem of material transportation (PFP) and the related sub-problems. Subsequently, documents regarding the AMR component and challenge related to AMR navigation in production environment were researched.

b. *Company visit*: From the company visit, it was possible to closely observe the functioning of the AMR and the critical issues in its operation within the working environment. The information gathered during the company visit comes from an initial presentation given by the managers about the automation of internal material transport and from the visit to the production department. The information collected was then used to help answer the first research question.
c. *Framework development*: Based on the insights gained from the literature, a theoretical framework was developed. This framework will outline the essential components that need to be considered in the PFP. The focus in the framework is on the transport component especially on AMRs characteristics in the transportation of material.
d. *Identification of environmental factors*: The literature review and the framework development will aim to identify critical factors that could affect the operation of AMRs in the intralogistics environment.

2.1.2 Quantitative

In general, quantitative analysis is employed to explain phenomena based on the analysis of numerical data derived from statistical methods (Yilmaz, 2013). Quantitative analysis in this project is used to help answer both research questions. To achieve this goal, the tool used in quantitative analysis is simulation software (FlexSim). FlexSim provides a dynamic and customizable platform for creating realistic simulations of material handling systems and robotic operations (FlexSim). Simulation is employed to: Evaluate the performance and efficiency of AMRs in material transportation within the production environment and compare them with traditional transportation systems.

2.1.2.1 Simulation based quantitative analysis

To achieve the objectives of quantitative analysis, through simulation software, two different scenarios are created and tested. From these, information and data to be analyzed are derived.

Once the data from the Swedish company that is the subject of the case study has been received, the data will be analyzed in Excel to determine the number of daily transport orders and set up the creation of the simulation model. However, before moving on to the creation and simulation of the two scenarios, once the data on the flow of materials has been obtained, the theoretical number of AGVs is calculated. This will then be compared with the number derived from the analysis with Flexsim. The phases constituting the simulation process are as follows:

a. *Model creation*: Model creation is the initial and crucial phase of the analysis. It is based on inputting real data from the Swedish company and the statistical analysis of the data from the material flow. The data include:
   1. Material flow: Information on quantity and frequency of material transport for some station of the production environment which will be served by the transport system (AMR and Forklift). The data are acquired from a database in a excel file sent by the Swedish company and calculation and elaboration of the data will be done to determine the delta between one order and the next one. Once the data for each station are calculated, a statistical analysis it will be done to identify the statistical distribution that better approximate the data. This will be made with a dedicated statistical software call Minitab. Minitab is a statistical software that could analyzed and visualized different type of data to allow a decisional process by data-driven. Once the data are analyzed for each station, the result of the statistical analysis is used to set up the processing time of the machine in the simulation model.
   2. Production layout: Site layout, including storage areas, workstations, transport paths and fixed obstacles. These data are acquired from a CAD file sent by the Swedish company and imported in the simulation model to respect the real distance of the industrial environment.
   3. Vehicle information: Technical specifications and performance of both traditional vehicles and AMRs are acquired. Speed, acceleration, deceleration, unload time and load time and carrying capacity are the technical specification derived.
b. *Scenario 1 simulation*: In this scenario, the transport of material using the AMR is simulated. The goal is to determine and measure the key performance indicators (KPIs) of the AMR and the machines and then compare them with scenario 2. The KPIs for the machines are: waiting for transport and processing while for the AMR they are idle time, travel empty, travel loaded, unloading and loading. They will then be introduced and explained in detail in chapter 4. Within this scenario, several simulations will then be performed by varying the transport orders and making the robot interact with the operators. The purpose of other simulations of the scenario is on the one hand to understand to what extent an AMR is sufficient to satisfy the transport orders and on the other to see if the interference with a task assigned to the operator affects the system performance.
c. *Scenario 2 simulation:* In scenario 2, the AMR is replaced by a traditional forklift currently used by the company to handle the analyzed transport orders. As for the AMR scenario, the

KPIs are measured for both the vehicle and the machines in order to be able to make a comparison between the two scenarios.

d. *Data collection*: Data are automatically collected by the software during the simulation of each scenario. The collected data pertain to the KPIs used to monitor the two scenarios. The KPI are acquired with a tool inside Flexsim call state tables that measured the state in percentage of the state of the AMR and the machine during one work day (two shift) that start at 6 am and finish at 22 pm. The data acquire from the software is organized in excel and then visualized with barchart the show in a better way the data to be used to make the comparison between the two scenarios.

e. *Quantitative Data Analysis*: Once the data are collect with the state table in Flexsim the result of the two scenarios are compared in excel. In this way we could create different chart and diagram to visualized and analyzed the data from which the conclusion are derived.

2.2 Methodology framework

This research thesis is mainly divided into two parts: a first part linked to the exploration of the intralogistics industrial environment and the PFP to determine which factors of the intralogistics environment in the PFP can influence the performance of the AMR and a second part linked to the comparison between AMR and forklift to make a comparison in terms of performance between the two vehicles. In figure 2.1 the methodology framework on which this thesis is based is represented. On the right side we have the methodological process to answer the second research question while on the left we have the description of the process to answer the first research question.

The answer to the first research question (RQ1) is carried out through qualitative analysis based on the analysis of the literature and on the observations made during the company visit. The blue arrow in figure 2.1 indicates that we want to find which characteristics of the industrial environment influence the functioning of the AMR and not vice versa. To this end, a theoretical framework is built to explore the intralogistics environment in the PFP and therefore answer the first research question and subsequently show the results (in chapter 3).

To answer the second research question, a completely different approach is used, namely a quantitative analysis through the use of a simulation software, namely Flexsim, to make the comparison between AMR and traditional vehicles (double arrow indicates the comparison between the two means of transport). The comparison is made through the analysis of KPIs used for both the machines and the AMR in the two simulation scenarios that see the AMR (scenario 1) and the forklift (scenario 2) used as means of transporting the material. The results will then be presented in chapter 4 dedicated to the case study.

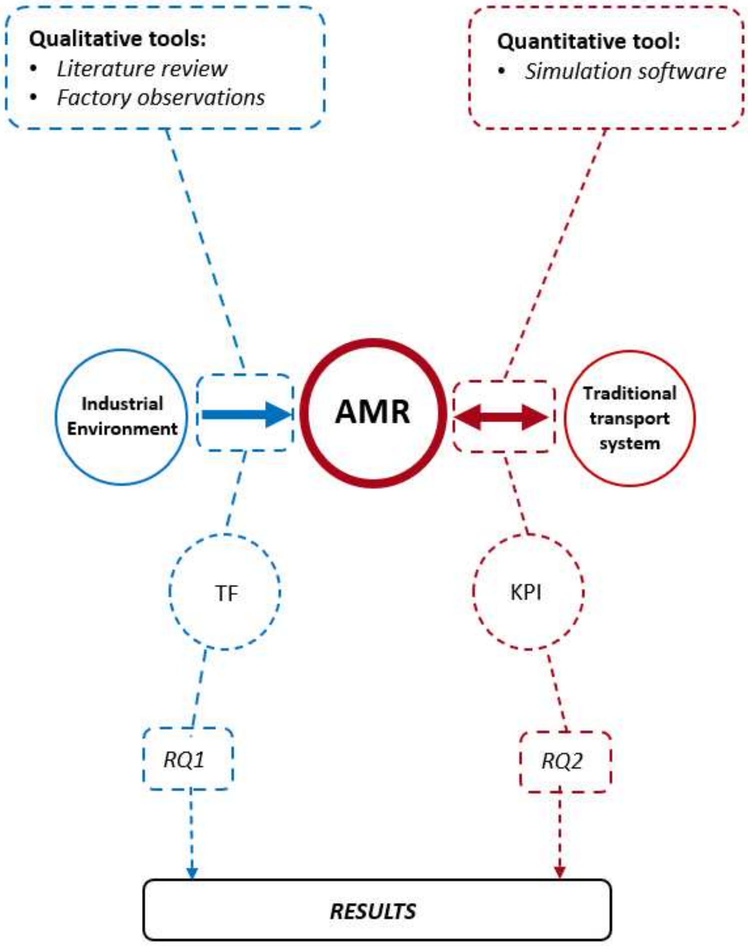


Figure 2.1: Methodology framework

3. THEORETICAL FRAMEWORK

This theoretical chapter aims to provide the foundation for addressing the case study presented in Chapter 4. The part feeding system, in an assembly-to-order (ATO) environment with mixed-model-assembly-lines (MMALs), will be broken down and defined into three sub-problems: storage, transport, and feeding policies. Each of these sub-problems will be discussed in separate sections in this chapter. In section 2.1, the main types of component storage in assembly-to-order (ATO) companies will be described. Section 2.2, the choices for deciding the suitable feeding policy for material delivery to the lines will be discussed. Finally, in Section 2.3, after introducing the characteristics of traditional and flexible transport systems, will describe the use of automated guided vehicle (AGV) in the part feeding system. In particular, the focus will be on a class of AGV called autonomous mobile robots (AMRs). After introducing the major components of the AMRs, several environmental factors that could affect the performance of the AMR, finding from the literature analysis, will be discuss to contribute to the response of the research question number one (RQ1).

Mass customization in industry has triggered a significant increase in the number of components variants in the past decade. To address the challenges associated with mass customization, such as frequent product changes and lower demands for individual products, assembly systems must become more flexible, adaptable, and agile (Adenipekun et al. 2022).The adoption of mixed-model assembly lines (MMALs) has become common among companies to enhance competitiveness in the market. However, this has resulted in an urgent need to improve part feeding performance in MMALs, as this process directly impacts overall assembly efficiency. Managing material supply poses one of the primary challenges associated with mixed-model assembly lines due to the large quantity and diversity of components required in final assembly.

Within a manufacturing environment, various production and assembly activities take place. After production, components are stored in dedicated storage areas and subsequently delivered to the assembly lines. The activities related to delivering materials to the assembly lines fall within a complex problem known as the line feeding problem (LFP) or part feeding problem (PFP) (Zangaro et al., 2020). The PFP involves defining how parts constituting the final product are brought to the correct assembly line, in the right position, and within a limited time. The activities involved in the PFP are related to the choice of component storage type, transportation means, and feeding policy (Battini et al., 2015). The performance and efficiency of assembly lines depend on the availability of parts and subassemblies that must be delivered at the lowest cost (Battini et al., 2015). Therefore, the part feeding problem (PFP) is one of the primary challenges that designers and managers must address when designing an assembly line (Caputo et al., 2016; Battini et al., 2015).

An overview of the part feeding system to assembly lines is presented in figure 3.1. In accordance with Battini et al. (2015), the feeding problem can only be resolved if three main sub-problems are addressed, which involve selecting the type of storage, identifying the means of transportation, and determining how assembly components are presented to the lines, namely the choice of feeding policies.

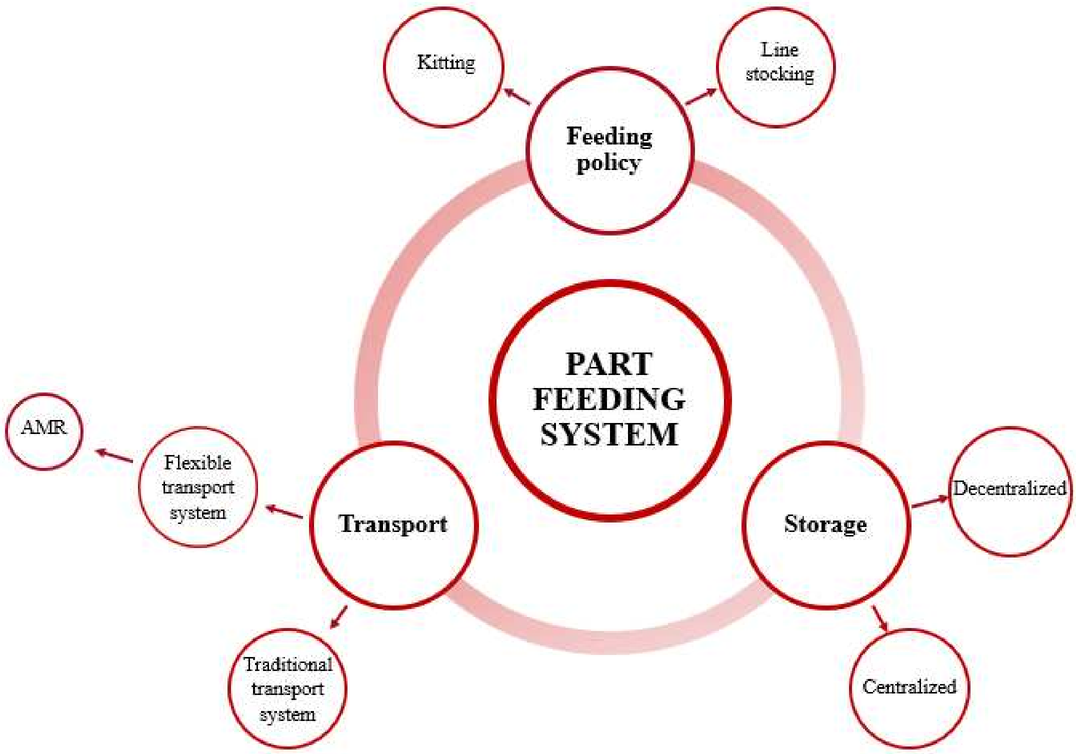


Figure 3.1: Overview of the part feeding system

3.1 Storage

In this section, the main types of storage for components and subassemblies for manufacturing companies will be described, particularly for companies where the market response is assembly-to-order (ATO). In these companies, the coupling between storage areas and assembly systems (assembly line or single station assembly system) is fundamental and critical because it directly affects the performance of the assembly system and the quality of the assembled products. In different assembly systems, products can be made of the same components, which are stored and supplied in different ways. The function of components and sub-assemblies inventories within a production plant is to keep production and assembly lines operating efficiently, and the choices of inventory level, supply methods, and warehouse locations greatly impact global production costs (Battini et al. 2010). The storage mode for the parts (needed for the assembly of the final product) can be primarily of three types: Centralized, decentralized with use of the supermarket and direct assembly station warehouse.

3.1.1 Centralized

A central warehouse is used for the storage of all components, purchased from suppliers and produced by other lines, figure 3.2. Parts are directly supplied from the central warehouse to the assembly lines, resulting in increased transportation costs due to long distances but a decrease in on line space usage. Most original equipment manufacturers (OEMs) nowadays strive to implement just-in-time (JIT) strategies to maintain sufficient supplies for final assembly while minimizing work-in-process inventory (Embde & Boysen, 2012). However, due to the extensive range of products and resulting diversity in parts, effective internal logistics become particularly vital to maintain competitiveness, especially since storage space at assembly stations tends to be both limited and costly. This centralized approach to part supply somewhat contradicts the JIT principle (Embde & Boysen, 2012). Firstly, because stations are supplied individually and from a potentially distant central store, parts must be delivered in sizable batches to prevent uncontrollable shop-floor traffic. Consequently, this leads to an increase in in-process inventory and accelerates reorder dates. Secondly, once delivered, pallets must be stored at the stations, where space is typically constrained, potentially impeding workers and decreasing productivity. For this reason, more and more ATO companies are adopting the use of the concept of a “supermarket” as a component storage policy.

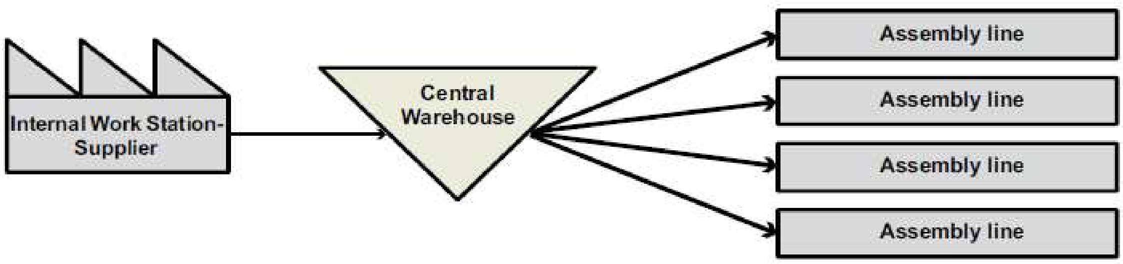


Figure 3.2: Centralized storage mode (Battini et al. 2010)

3.1.2 Decentralized with the use of a supermarket

The supermarket is a simple warehouse (containing a few units for each part) located within the facility at a short distance from the assembly lines, Figure 3.3.

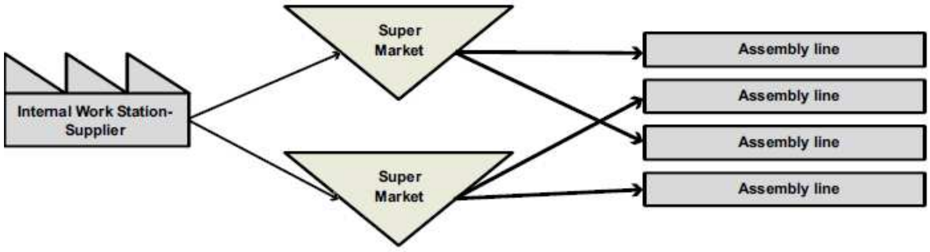


Figure 3.3: Decentralized type mode with supermarket (Battini et al. 2010)

It allows for the decoupling between the assembly lines and the central warehouse, which sends components to the supermarket when it falls below a certain reorder level. Furthermore, the supermarket must contain all the product mixes necessary for assembly. Supermarkets are utilized similarly to "food supermarkets," where warehouse operators, like customers in a food supermarket, navigate aisle shelves to gather the parts required for assembly, (Battini et al. 2015), as shown in figure 2.4. In the supermarket, operators can access components in an ergonomic and efficient manner, thereby reducing the effort and time required for part handling.

Figure 3.4: Example of supermarket (Battini et al., 2010)

This type of storage has been essential for assembly-to-order (ATO) manufacturers to maintain production systems and assembly lines at an efficient operational level and to ensure the right flexibility to demand variability.

The benefits of implementing the supermarket concept include quicker delivery times due to proximity to the assembly line, consolidation of freight through industrial truck supply, and increased turnover by stocking and delivering parts as needed. Additionally, frequent small-lot deliveries facilitated by supermarkets offer flexibility for replanning, whereas large-lot deliveries are challenging to adjust, particularly in the face of unforeseen disruptions. Moreover, storing comparatively small bins in easily accessible racks near the assembly line allows workers to retrieve parts in an ergonomic and efficient manner, reducing handling times and minimizing strain on the workforce (Embde & Boysen, 2012). However, there are drawbacks to consider. Supermarkets occupy valuable space on the factory floor, which is both limited and costly. Furthermore, effective implementation of the supermarket concept entails investment in equipment, staff, and maintenance.

The supermarket replenishment process is a complex operation involving various systems of the company's internal logistics organization. In general, these systems include the central warehouse that supplies the missing parts to the supermarket and the vehicle network that replenishes parts to the assembly line. In this way, the supermarket creates a decoupling point because suppliers and facilities deliver parts to the central warehouse, and only the supermarket is synchronized with the assembly line's pace (cycle time or takt time of the line). Within the supermarket, operators can freely move to pick parts from the shelves and sort them once the empty vehicle has arrived at a designated stopping area (depot) following a parts request from the lines. Subsequently, based on a picking list, the operator fills the bins that will be taken onboard the border of the line (BoL). In some cases, components must be placed inside containers to respect the assembly sequence, following the principle called just-in-sequence (JIS). At this point, the vehicle leaves the depot and, following a milk-run-based delivery system, visits various stations in a precise sequence and time. Finally the empty vehicle return to the depot and the procedure start again. Figure 3.5 shows a general supply process.

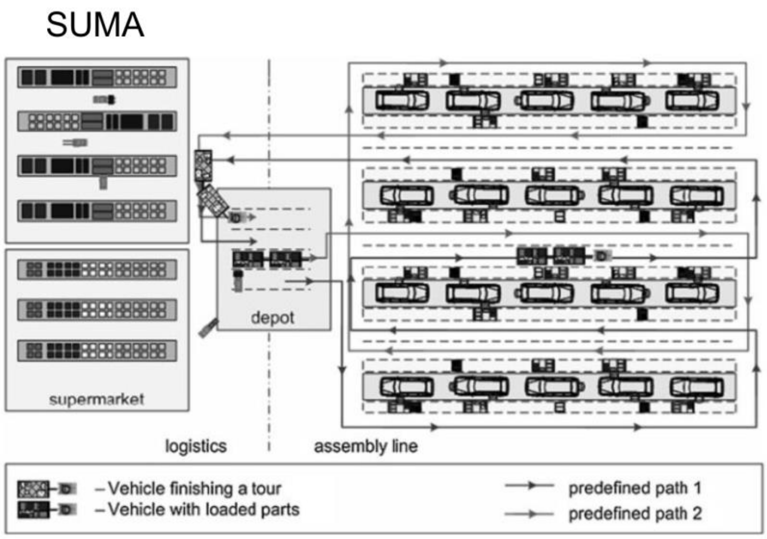


Figure 3.5: Supply process with supermarket (Golz et al.,2011)

3.1.2.1 Type of supermarket

To meet various production needs and different assembly lines, like the variety of the production mix, over the years, different forms of supermarkets have been developed (Battini et al. 2015):

1. *Single-line supermarkets:*
   This is the simplest configuration, see figure 3.6. A specific area of the supermarket is dedicated to the assembly line, and a series of autonomous or manually operated vehicles perform a certain number of milk-runs per shift to supply parts to the line. The efficiency of the part delivery process is maximized when the supermarket is close to the assembly line.

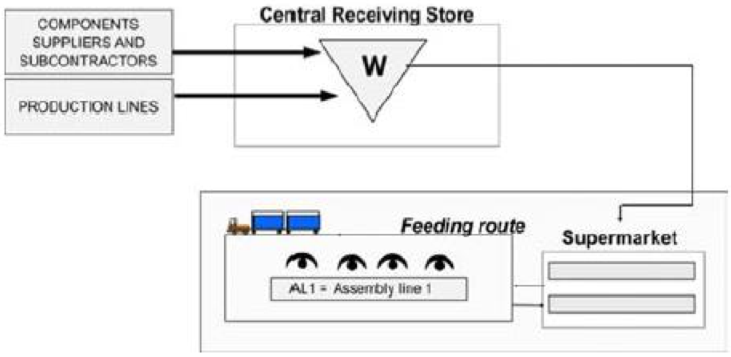


Figure 3.6: Single line supermarket (Battini et al. 2015)

2. *Multi-line supermarkets:*
   When different supermarkets share a high percentage of common parts or when space is limited, it is convenient to have a single area dedicated to the supermarket, which in this case contains parts for two or more assembly lines, figure 3.7.

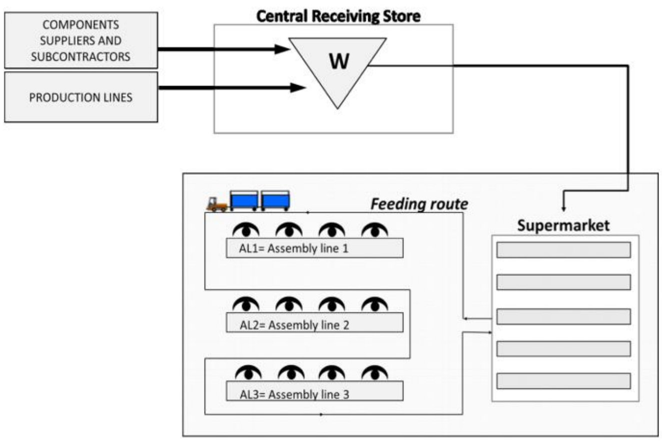


Figure 3.7: Multi-line supermarket (Battini et al. 2015)

It is worth noting that these two types do not occupy space near the assembly station where space is generally limited. It is also noted that within the facility, there may be more than one supermarket feeding one or more lines in accordance with the two types listed above. In this case, they will be referred to as multiple supermarkets. These multiple supermarkets are generally more decentralized than the two types listed above and less specialized than the fish-bone supermarkets.

3. *Fish-bone supermarkets:*
   This type is conceptually different from the first two; in fact, these are supermarkets integrated with the line and are therefore directly positioned behind the assembly stations. The name is inspired by the shape these supermarkets create, which resembles that of a fishbone, figure 2.8. This typology is widely used for MMALs (Mixed-Model Assembly Lines) as it allows for the optimization of the assembly of bulky and high-value parts.

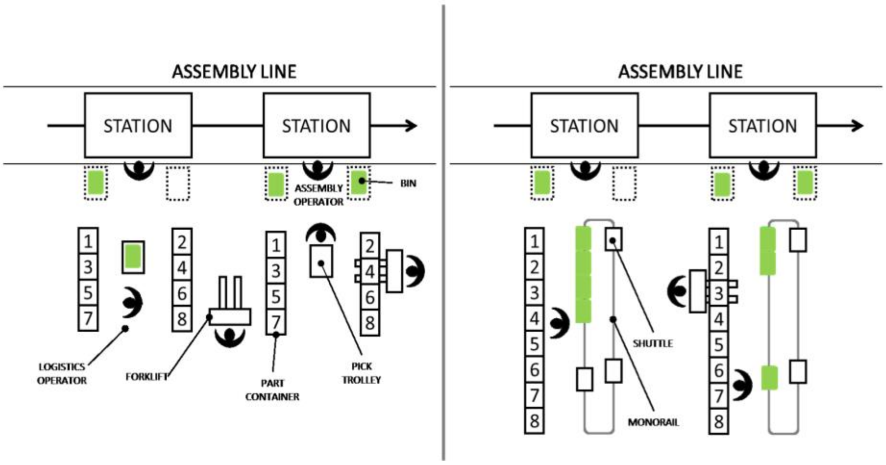


Figure 3.8: Fishbone supermarket (Battini et al. 2015)

3.1.3 Direct assembly station warehouse

Typical solution obtained when an external supplier or an internal workstation supplies directly the assembly station without intermediate warehouses, figure 3.9. The advantages of this system are: lower procurement time, lower quantity of workstations refilling, and lower transport frequency.

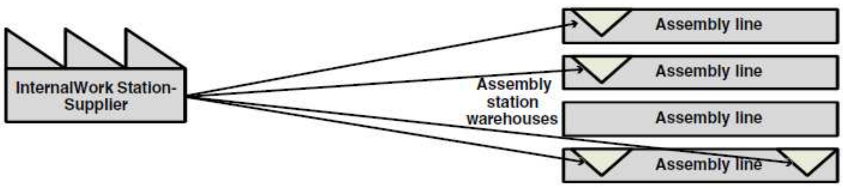


Figure 3.9: Direct assembly station warehouse (Battini et al. 2010)

3.2 Feeding Policy

An assembled product consists of a series of parts and subassemblies that, when combined, form a finished product. In the design and management of an assembly line, decisions must be made regarding how components and subassemblies are delivered to the assembly stations (Caputo et al., 2016). To address this issue in terms of cost reduction and line performance improvement, line feeding policies are employed. These policies dictate how a number of parts or a family of parts is delivered to the border of the line (BoL) in terms of packaging, racks, volume, weight, part numbers either individually or in a defined kit or sequence (Baller et al., 2020). Each feeding policy is characterized by the specific manner in which it handles the four fundamental processes associated with line feeding, as illustrated in Figure 3.10: part replenishment, preparation, transportation, and usage at the assembly stations (Adenipekun et al., 2022).

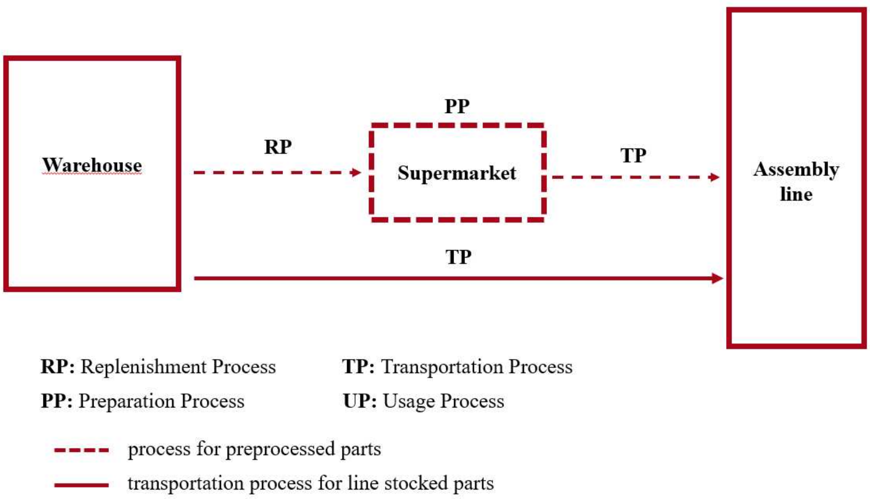


Figure 3.10: Four fondamental process related to line feeding policy

In accordance with Baller et al. (2020), it is possible to distinguish two main groups of feeding policies: Line stocking and kitting

1. *Line stocking:*

   In line stocking, a batch of identical and multiple parts of medium or small size is brought to the BoL, see figure 3.11. The parts come directly from the central warehouse without passing through the supermarket, and generally, they are brought to the line in the same container (pallet or boxes) in which they are delivered by the supplier (Baller et al., 2020). Therefore, this is the only policy in which replenishment and preparation of parts are not necessary. However, the operator will have to perform the part identification, walking, and picking operation at the line. To request the delivery of line stocked components, it is possible to use a kanban signal or a consumption renewal method according to the just-in-time (JIT) principle (Zangaro et al., 2020). When an order for a line stocked component is generated, the entire unit load is delivered to the station, and only when it is empty will it be transported back to the central warehouse to make space for components of the next order (Battini et al., 2009). This strategy is useful when the entire unit load is fully utilized by the station so that there is no need to return it to the warehouse. In general, the disadvantages of this technique are that the space occupied at the BoL is high, it requires several operations by line operators, and furthermore, the right quantity of necessary parts is not delivered but rather the entire unit load. This fact increases total transportation costs because the entire unit load is moved back and forth between production and the warehouse (Battini et al., 2009).

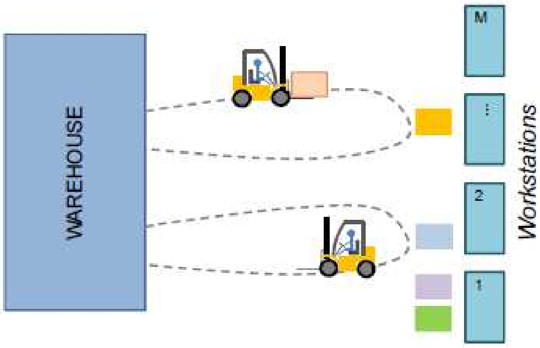


Figure 3.11: Scheme of line stocking system (Caputo et al., 2015)

2. *Kitting*

In kitting, at the production line, only a specific number of various pieces intended for assembling one or a few components of the final product are delivered. When kits are used, different parts are introduced into a container according to the assembly line sequence. The production scheduling determines the number of kits needed from the warehouse during a specific period of time and the number of prepared kit is exactly equal to the number of end-products for each work station (Battini et al., 2009). The kitting activity involves kit preparation, its transportation to the production line, and picking the necessary parts. There are different way to prepare a kit, in general kit preparation takes place at a dedicated area (usually at the supermarket), where the kitting operator begins by checking a detailed list of the number of parts, quantities of parts, and the number of kit containers, along with instructions on the arrangement of parts. Subsequently, the operator sets up a cart with the appropriate number of empty containers for the kit and moves within the supermarket to collect the ordered parts. Depending on the number of containers required for the kits and the cart's capacity, the operator may need to make multiple rounds in the supermarket. Each picking phase in the supermarket involves identification and subsequent acquisition of parts. In this situation, two different kit preparation options are outlined:

- Stationary kit:

  It is delivered to a specific assembly station and remains stationary at that station until the contained part is used. This type of kit is often employed with a technique known as just-in-sequence (JIS), where multiple parts sequenced based on their usage, as defined by production, form the "station kit" (Battini et al., 2015). However, this system is inflexible to changes in the production mix, and therefore, in these cases, a traveling kit is preferred.
- Travelling kit:

  It moves along the assembly line from station to station along with the workpiece, see figure 3.12. Throughout the line, various components of the kit are used by operators to assemble the final product. Since the kit already contains all the parts needed for assembly, the activities of searching for parts and identification can be neglected, leaving only the picking activity.

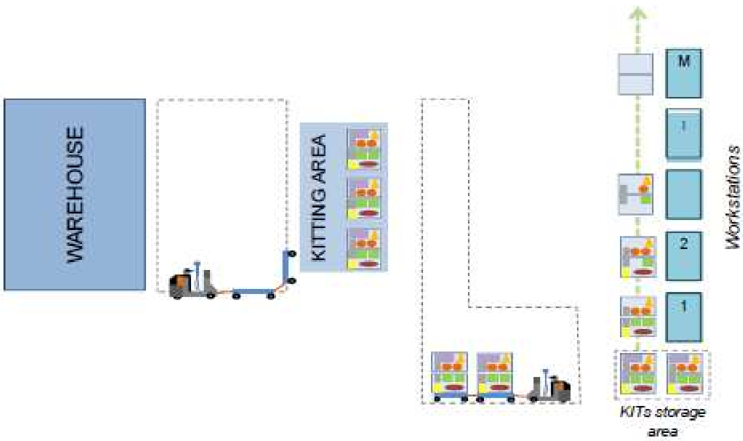


Figure 3.12: Scheme of travelling kit system (Caputo et al., 2015)

3.2.1 Choice of the feeding policies

With the increase in mass customization of products, the number of product variants has risen (Baller et al., 2020). This has led to an increase in line feeding policies over the last decade. Therefore, in addition to the feeding policies just mentioned, there are either hybrid approaches of the presented policies or an adaptation of them.

Each policy has its own advantages and disadvantages, making it difficult to definitively declare one feeding policy as superior to others in a general sense. Factors such as cost considerations, specific requirements, and constraints of each case may favor one option over others within an assembly system. Therefore, selecting the most suitable parts feeding method becomes a significant decision-making challenge. This decision often involves qualitative assessment influenced by various factors such as product and production system structure, operational limitations, company-specific practices, and traditions, yet it significantly impacts assembly system performance. While the primary trade-off typically involves labor cost versus space occupation and work-in-progress (WIP) holding cost, additional factors such as quality control degree, assembly support, flow control, visibility concerns, ergonomics, material security, obsolescence, compatibility with diverse product varieties and frequent mix variations, ease of implementation, etc., may favor one policy over another within a specific manufacturing context (Caputo et al., 2016).

The choice of feeding policy has been widely discussed in the literature. For example, Baller et al. (2020), in their model aimed at solving the assembly line feeding problem (ALFP), consider nine different line feeding policies (just-in-sequence, large load carrier, small load carrier, supplied in flow rack, sequencing, small stationary kit, traveling kit, line side repackaging, and large stationary kit) to minimize the costs associated with line feeding activities and analyze a case study. Zangaro et al. (2021) consider as feeding policies line stocking, kitting and sequencing and use the use the Classification And Regression Tree (CART) algorithm to develop, in a supervised way, a decision tree based on problems that are solved with a Mixed Integer Programming (MIP) model. Based on selected attributes of the components (number of variants of component, volume of a box of the component, volume of a component, depth of a box component, length of a box component, weight of a box of a component and weight of a component) and the manufacturing environment, the decision tree suggests a line feeding mode for every component. Caputo et al. (2016) developed a cost model where a sensitivity analysis is conducted. The study aims to explore the impact of part features, such as unit size and cost, on the total delivery cost of materials to assembly line workstations, which is considered as a criterion for directly selecting the feeding method for each type of part. The feeding policies used in this study are kitting, line storage/line stocking, and just-in-time delivery. The analysis results indicate that policy selection should consider the simultaneous economic impact of all part attributes, as different attributes may lead to different optimal choices. They provide a table, figure 3.13, that illustrates a sample discrete mapping for different ranges of part attributes. Each cell of the table displays the minimum cost feeding policy for each considered triple of attribute values.

C	5			25			45			200		
W / V	0,5	2,5	4	0,5	2,5	4	0,5	2,5	4	0,5	2,5	4
0,5	J	J	L	J	J	L	J	J	L	K	K	L
2,5	J	J	L	J	J	L	J	J	L	K	K	L
4	J	J	L	J	J	L	J	J	L	K	K	L
20	J	J	L	J	J	L	J	J	L	K	K	L
Legend: W = item weight (kg/item); V = item volume (cm^3 x 10^4/item); C= unit cost (€/item); J = JIT; L = Line Storage; K = Kitting												

Figure 3.13: Mapping of economic policies

A study conduct by Battini et al. (2009) describes an integrated approach to component management optimization within a production/assembly system. A framework, depicted in Figure 3.14, is proposed, consisting of a series of key decisions to be made in order to choose the best solution for the assembly feeding system and its management for make-to-order (MTO) or assembly-to-order (ATO) companies.

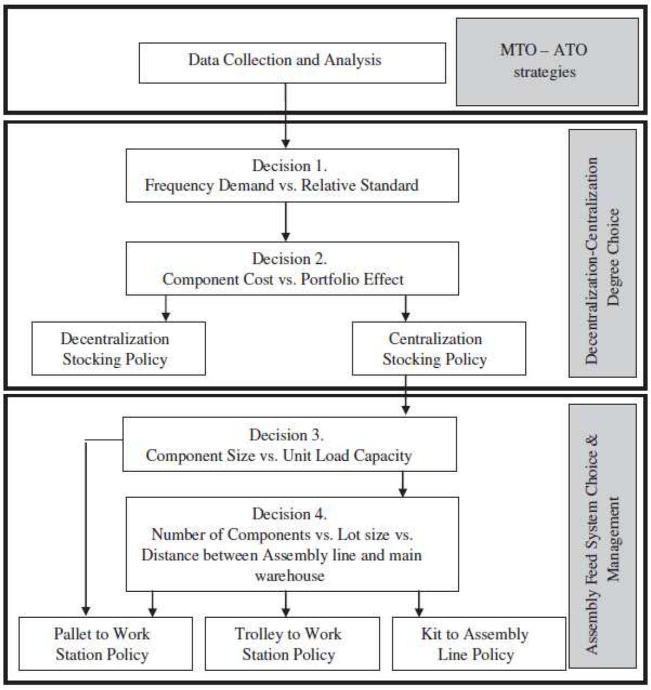


Figure 3.14: Integrated methodological framework (Battini et al. 2009)

The considered feeding systems are: pallet to work station, trolley to work station (where storage warehouse operators gather and prepare components to be delivered to the lines via a tugger train), and kit to assembly line.

The decisions to be made for the selection and management of the assembly line feeding system are two: Decision 3 and Decision 4.

- *Decision 3-Component size vs unit load capacity:*
  To make this decision, one must know:
  - The average quantity of components picked for each row, R_h
  - The number of components in one specific item unit load, Q_p

  The relationship between these two values provides the number of components carried from the main stocking point to the assembly line, related to how many components are transported by each pallet. A high value of these parameter, typically between 0.7 e 1, show that when a component is requested by a production order, the required quantity is comparable to the quantity of the item in its item unit load hence it seems opportune to feed the assembly line with a pallet-to-work station policy. On the contrary, when the value of (R_h/Q_p) is low, the Pallet-to-Work station policy reveals inadequate, generating a high flow of partially full pallets from the main warehouse to the work stations and back. This situation can be solved moving to the following step: Decision 4 which takes into account several variable existing on the production line in the attempt to minimize the total time spent to feed the assembly line

- *Decision 4- Number of component vs lot size vs distance between assembly line and main warehouse:*
  At this point, an analytical model is used to define a total time function. This function represents the time required to replenish the line and is the sum of three different time components:
  - t_{ass} = time spent by assembly operators to manipulate all components
  - t_{carry} = time spent by picking operators to transport the components to the assembly lines
  - t_p = time spent by picking operators to gather the components within the warehouse

  The total time function is calculated as: $t_{tot} = K_c \times t_{ass} + t_{carry} + t_p$ where K_c represent the ratio between assembler cost and picker cost, considering also downtime costs. This function depends on different variables depending on the considered feeding system (pallet to work station, trolley to work station, and kit to assembly line). Therefore, a factorial analysis, ANOVA, is conducted to study the effect of different variables on the total time functions. From the analysis, it appears that the main factors influencing this function are:

  - Avarege assembly lot size

- Number of work station on the assembly line
- Distance between warehouse and assembly line
- Average number of components for each end-product

The principal factor that influences the convenience of the policies is the lot size, in fact when the lot dimensions are modest, the best feeding system is the kit to assembly line, while for high lot dimensions the best policy seemed to be the pallet to work station policy, while for medium-size-lots the best solution could be either trolley to work station and pallet to work station, depending on the number of work stations on the assembly line and the distance between warehouse and assembly line. The table in figure 3.15, that illustrates the most appropriate policy to adopt when the most important factor change.

	L		
	2	8	16
$L_{W\text{-}AL} = 50$ m			
N_c			
10	*K–AL*	P–*WS*	P–*WS*
20	*K–AL*	P–*WS*	P–*WS*
30	*K–AL*	P–*WS*	P–*WS*
$L_{W\text{-}AL} = 150$ m			
N_c			
10	*K–AL*	T–*WS* for $N <= 5$ *P–WS* for $N > 5$	*P–WS*
20	*K–AL*	*T–WS*	*P–WS*
30	*K–AL*	*T–WS*	*P–WS*
$L_{W\text{-}AL} = 300$ m *T–WS*			
N_c			
10	*K–AL*	*T–WS* for $N <= 8$ *P–WS* for $N > 8$	*T–WS* for $N <= 5$ *P–WS* for $N > 5$
20	*K–AL*	*T–WS*	*T–WS*
30	*K–AL*	*T–WS*	*T–WS*

Figure 3.15: Decision 4 (Battini et al., 2009): L = avarege assembly lot size, $L_{W\text{-}AL}$ = distance between the components main warehouse and assembly line, N_C = avarege number of components for each end-product, N = number of workstation in the assembly line

Another study conducted by Battini et al. (2015) provides a framework to support managers in making key decisions regarding the design of fully automated part logistics systems with a supermarket. The part feeding problem is broken down into three sub-problems: choosing the type of "supermarket," selecting the type of transportation, and deciding on the feeding policy, as shown in Figure 2.16.

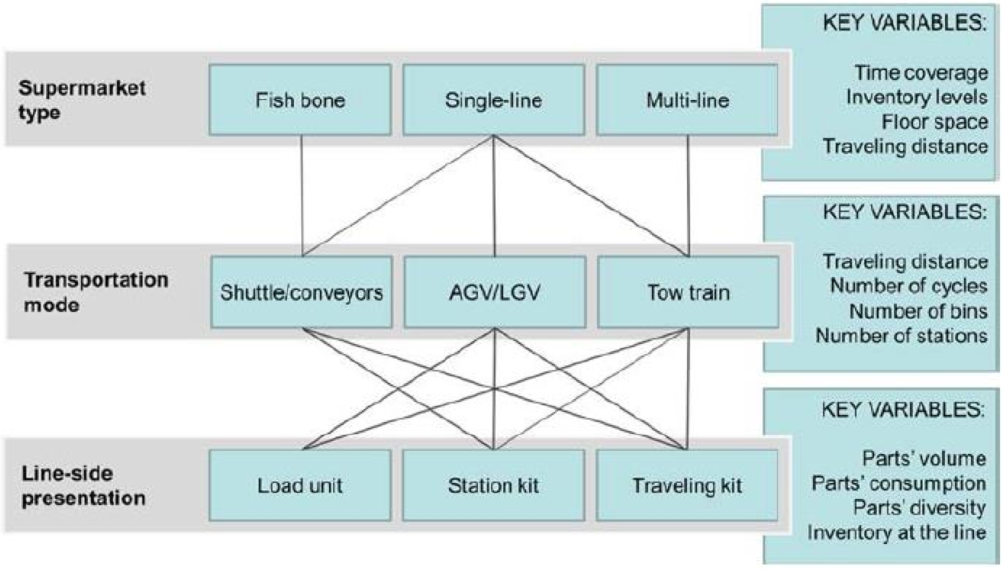


Figure 3.16: Framework to design a fully automated part logistics system with a supermarket (Battini et al., 2015)

These problems are closely interconnected, and each one contains key variables to make decisions about them. For the choice of the feeding policy, the following are considered: load unit (line stocking), station kit, and traveling kit. For an initial qualitative analysis of the feeding policy choice, it can be conducted by observing the volume occupied and the diversity in the assembly mix according to the tables in Figure 3.17.

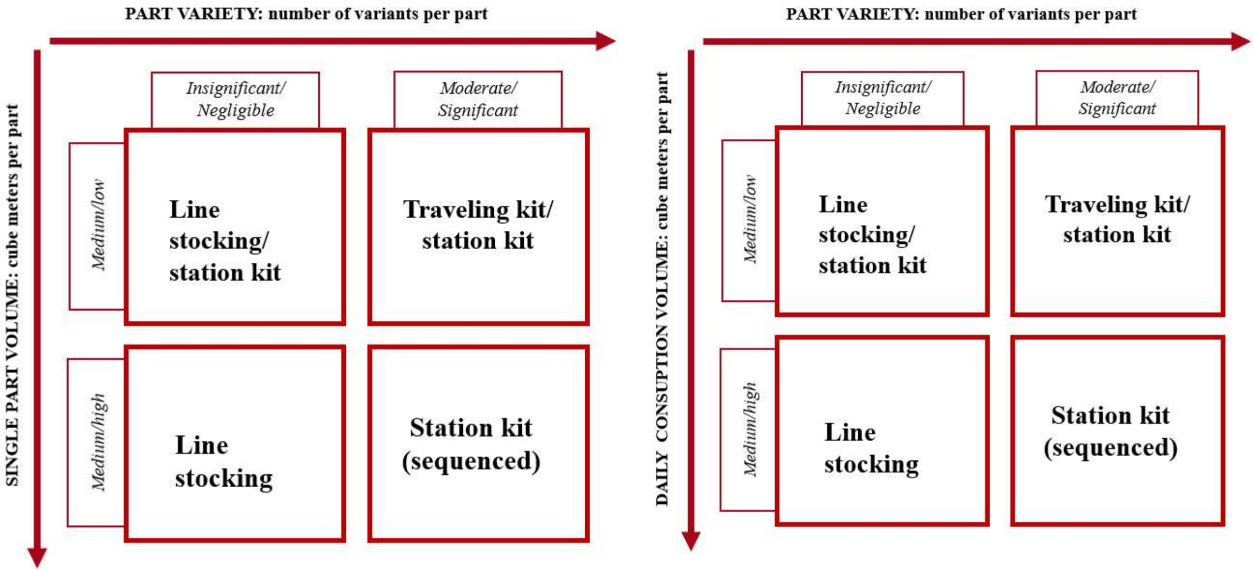


Figure 3.17: Quality maps for decision of the feeding policy (Battini et al. 2015)

From these two maps, it can be inferred that the station kit and the traveling kit solutions are typically preferred over the lot-wise load unit solutions for small parts with numerous variants and voluminous parts with numerous variants (typically greater than one).

3.2.2 Transportation mode selection

Regarding the choice of transportation mode, Battini et al. (2015) propose a quantitative method to evaluate and help in the preliminary decision-making phase based on the framework in Figure 3.18. Different kinds of transportation modes are taken in to account (shuttle, AGV and tugger train) in the single-line configuration, and the best choice depends on the four key variables:

- number of bins handled per station per time unit;
- number of meters traveled, which means the whole traveling distance;
- number of stations present on the line, which means the number of loading/unloading points in the feeding route together with the supermarket depot;
- number of assembly cycles to be performed in a time unit

An analytical cost models are defined for each transportation mode (calculated as the product of the number of vehicles required for part transportation and the unit cost of each vehicle) and adopted in a multi-scenario analysis to determine the boundary conditions that make the shuttle, the AGV or the tugger train profitable, varying the design parameters previously mentioned. The result of the analysis, resume in figure 2.3.9, show that smaller assembly lines (with a low number of stations) with a larger takt time will benefit from a shuttle conveying system, while longer lines with a shorter takt time (which means a high number of assembly cycles/hour) often need the tugger train concept. The economic suitability of the automated tugger train transportation system increases when the number of part bins handled per time unit increases and/or when the traveling distance increases. In the intermediate position, we can find the AGV, which are, from an economic point of view, convenient with respect to the tugger train only, when the number of stations on the line does not exceed 5.

			N								
DLS	S	B	24	12	6	3	2	1	0.6	0.5	0.3
50	5	2	TOWTRAIN	AGV	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE
		4	TOWTRAIN	TOWTRAIN	AGV	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	AGV	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE
	15	2	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	SHUTTLE	SHUTTLE	SHUTTLE
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	SHUTTLE
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	SHUTTLE
	30	2	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
100	5	2	TOWTRAIN	TOWTRAIN	AGV	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	AGV	AGV	SHUTTLE	SHUTTLE	SHUTTLE	SHUTTLE
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	AGV	AGV	SHUTTLE	SHUTTLE	SHUTTLE
	15	2	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	SHUTTLE
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
	30	2	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
200	5	2	TOWTRAIN	TOWTRAIN	TOWTRAIN	AGV	AGV	AGV	AGV	AGV	SHUTTLE
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	AGV	AGV	AGV	AGV	SHUTTLE
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	AGV	AGV	AGV	AGV
	15	2	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
	30	2	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		4	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN
		8	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN	TOWTRAIN

Figure 3.18: Decision support matrix supporting the transportation mode selection when an automated handling system is used and a supermarket store is present according to variations in the four key variables affecting the feeding system (Battini et al., 2015): N = number of assembly cycles in one working hour (number of takts of the line in one working hour), S = number of station of the line, B = number of bins demanded/consumed in a station during an assembly cycle/takt time, DLS = distance between line and supermarket

In conclusion the paper presented by Battini et al. (2015) reveals that the transportation system choice is strongly affected by four key parameters: number of meters traveled during the feeding process, the assembly line dimension, the assembly line takt time and the number of parts bins demanded by station per takt.

Another study regarding the choice of transportation mode in the feeding problem was conducted by Adenipekun et al. (2022). In this study, a mixed integer programming model (MILP) is introduced, aiming to assign each part simultaneously to a feeding policy and a vehicle type in an efficient manner, with the objective of minimizing total feeding costs. To precisely assess costs, the model identifies particular routes and establishes the fleet size for each type of vehicle utilized. The model is enhanced by valid inequalities and its effectiveness is confirmed through the resolution of artificial problem instances. Within the analysis, they demonstrate that optimal selection of vehicle types is superior to heuristic approaches and show that this optimization-based approach is around 8% cheaper than the industrial standard. From this study, it is also important to note that in the selection of the vehicle type for the feeding policy, all vehicles used in the analysis are employed (forklifts, AGVs, and tow trains). The results show that forklifts are the least utilized vehicles (less than 1% usage) by the feeding system due to their high acquisition and operational costs. Additionally, forklifts cannot serve more than one station at a time. On the other hand, AGVs and tow trains are more frequently used because they can serve multiple stations at once (in a milk run) and minimize empty trips. In general, Adenipekun et al. (2022) assert that even though some vehicles are underutilized, the optimal solution involves the use of all vehicles type in the feeding system.

3.3 Transport System

The focus of this section will be on flexible transport systems (AGV/AMR) within the part feeding problem. After briefly introducing the role of material transport within production systems, the main types of transport vehicles in in-bound logistics will be identified and analyzed. First, the characteristics of the most common vehicles, namely traditional material transport vehicles, will be listed and analyzed. Subsequently, flexible transport vehicles such as autonomous guided vehicles (AGVs) will be extensively discussed, starting from the more rigid systems represented by fixed-path AGVs, up to the latest generation systems, namely autonomous mobile robots (AMRs).

Material transport can be defined as an integrated system that incorporates activities such as handling, manipulation, storing, and control of materials using gravity, manual effort, and power-activated machinery (Tauseef, 2010). The transportation of material in intralogistics plays an important role affecting production efficiency and energy consumption. It takes care moving raw materials and final products from and to factory warehouse and the production shop floor: any bottleneck and inefficiency in factory logistics decreases the productivity level of the whole factory (Sabattini et al. 2013). Moreover, material handling is an area of significant interest in flexible manufacturing systems because the majority of the time spent by materials within the shop floor is dedicated to transport or waiting, even though these activities do not add value to the finished product. Therefore, an efficient transport system is crucial for reducing congestion, delivering materials on time, and decreasing machine idle time due to accumulation or unavailability of components at workstations (Tauseef, 2010). The transportation systems available today for material handling in intralogistics are diverse. However, the choice of the type of system to ensure handling needs to be made in relation to individual real-world cases, (Pareschi et al. 2011). In a preliminary analysis, according to Pareschi et al. (2011), transportation systems in intralogistics can be divided based on two fundamental aspects: Degree of automation and level of flexibility. From these, the following schema can be defined:

	Low flexibility	High flexibility
Low automation	Transpallet	Forklift
High automation	Rigid transports (Conveying system)	Automated guided vehicle (AGV)

From this framework, two main material transportation systems can be identified within intralogistics: traditional transportation systems and flexible transportation systems.

3.3.1 Traditional transport system

The main traditional material transportation systems in intralogistics are:

- Transpallets and Forklifts:
  These are wheeled vehicles used for the movement of materials of any kind with the intervention of operators on the ground or aboard the vehicle itself. They mainly come in small-wheeled carts for small lifts (transpallets), figure 3.19, which lift the load only for transport purposes, and stacker trucks, equipped with suitable equipment to lift the load to higher heights. There are different types of stacker trucks, which differ in terms of dimensions, speeds of movement, and lifting height of the load. Among stacker trucks, the most versatile and economical is the front forklift, figure 3.19. The advantages of this transportation system are high speed and ease of maneuverability; among the disadvantages are the space required for passage in aisles and the limited lifting height (5 or 7 meters). Additionally, this type of forklift is often used for material handling in intralogistics, meaning the transport of load units from the storage point (typically the warehouse) to workstations within the production or assembly area.

Figure 3.19: Forklift transport system: Transpallet on the left and a front forklift on the right

- Conveying Systems:

  There are different types of conveyors that vary based on the material transport mechanism (roller conveyors, belt conveyors, shutter conveyors, etc.) and the type of material being transported (individual packages or bulk material), Figure 3.20 show an example of roller conveyor. The use of these systems is diverse, ranging from intensive warehouses to production. An example is the use of roller conveyors as basic elements of entry and exit docks in automated warehouses, or the use of belt conveyors in production for transporting materials from one station to another. In general, these systems are rigid, follow a fixed and unchangeable path, and therefore are not flexible to layout changes.

Figure 3.20: Example of a roller conveyor (https://www.nai-group.com/conveyor-system-technology-trends/)

3.3.2 Flexible transport system

Currently in the world of consumer society, where the corporations which are seeking to improve work efficiency, minimize the cost of human operators in logistics, and also bring the production cycle time down, make an accurate utilization of robots can promote the operation of the working process by simplifying it to greater extent. Such progress is rendered by Automated guided vehicle AGV (Sankari & Imtiaz, 2016). The introduction of these vehicles has allowed industries to increase efficiency and reduce costs by helping to automate manufacturing facilities or warehouses. According to Sankari & Imtiaz (2016), an AGV, or Autonomous Guided Vehicle, is a self-operating transportation system (requiring no operator intervention) primarily used by companies to transport various materials from point A to point B, both within and outside the factory premises. The main industrial sectors that utilize this type of material transportation system include aerospace, automotive, electronics, food, paper, pharmaceutical, healthcare, and textile industries (Pareschi et al., 2011). AGVs used in material handling can be equipped with forklifts for pallet handling, tow a series of carts with various materials, or be fitted with lifting devices to raise entire shelves of materials. When we refer to AGVs, we're talking about a broad category of automated guided vehicles that includes various classes of vehicles. In a preliminary analysis, we can divide autonomous guided systems into those with fixed paths and those with variable paths. Fixed path guidance systems require the installation of a track on the floor, which depends on the vehicle's guidance technology, see figure 3.21. Fixed-path guidance systems can use optical, inductive, or mechanical guidance. Optical guidance relies on a photosensitive or reflective strip applied to the floor, inductive guidance uses a multipolar cable embedded in the floor, while mechanical guidance involves the vehicle moving on a rail. Regardless of the navigation technology, it can be said that these AGVs "follow" a path, making them the least flexible type of system to production changes.

Figure 3.21: Example of fixed path AGV supported by photoelectric sensors (https://www.turck.in/en/rfid-guides-agv-in-suspension-production-6880.php)

3.3.2.1 Variable path guidance systems

Modern AGV differ from the conventional ones, instead of using fixed paths many modern AGVs are free-ranging. Thus their preferred tracks are software programmed, and can be changed fairly easy when new stations or flows are supplemented (Sankari & Imtiaz, 2016). These systems are the most flexible but, on the other hand, require mapping of the working area and reference points. These latter systems do not follow a predetermined path but "choose" a route. There are various types of AGVs with variable path capabilities, differing based on the guidance system technology (Pareschi et al. 2011):

- Cartesian reference guidance:
  The vehicle uses a Cartesian grid reference and special sensors to detect X and Y coordinates to orient itself and determine its specific position.
- Inertial guidance:
  This system comprises a gyroscope, a wheel with odometry functions, and magnetic sensors. The gyroscope determines the vehicle's direction, while the wheel's revolutions are counted by encoder-like systems to measure distance. To move within the work environment, the AGV is equipped with magnetic sensors to recognize magnetic plates positioned along the path as reference points. Information from detecting these plates is transmitted to the onboard navigation system to determine and correct the vehicle's position if necessary.

- Camera guidance:
  This guidance is used for special applications requiring tight tolerance in the interface between the vehicle and other devices.
- Laser guidance:
  A laser signal emitted from a rotating laser head mounted on the vehicle hits multiple reflective targets (at least three) positioned along the path, see Figure 3.22. The reflected signal is captured and processed by the onboard computer, which interpolates data on distance and reflection time to determine the vehicle's position within the workspace. For optimizing internal transportation in an industrial environment, this guidance system represents the ideal solution as it offers maximum flexibility. Maximum flexibility is ensured through the use of a simulation system for studying and designing the plant. Through this system, layouts, trajectories, the number of executable missions, and the number of required vehicles are analyzed.

Figure 3.22: Example of free path AGV (forklift AGV) with laser guidance (https://bluebotics.com/agv-navigation-methods-virtual-path-following/)

Within the Part Feeding Problem (PFP), AGVs system are used for material transport between the storage area and various dedicated drop-off zones within the production or assembly zone.

Missions in the AGV system, according to Sabattini el al. (2013), are divided into:

- *AGV journeys*
  From the perspective of an AGV, a task consists of a series of route map segments to traverse. Consequently, upon receiving a task assignment from the central controller, the AGV must adhere to a predetermined path to reach its destination. During navigation within the route map, the AGV must continuously monitor its position relative to the global reference frame.
- *Unit load handling*

Every trip undertaken by an AGV aims to transport a unit-loads of goods from one location to another. Consequently, loading and unloading tasks must be carried out at both the start and end of each trip. Additionally, during transit with a loaded unit, AGVs must maneuver in a manner ensuring the cargo remains secure without contact with external objects. In this context, we can divide AGVs based on the type of load they transport, which can be a single unit load or multiple unit loads. Therefore, we can have:

1. Single load AGVs:
   In this case, the AGV transports a single unit load, which can be a pallet or a rack. Both the rack and the pallet can contain various components, whether of the same type or not, depending on the feeding policy adopt. The choice to transport a single load unit depends on the characteristics of the material to be supplied, its quantity, and the available space for maneuvering the vehicle.
2. Multiple load AGVs (tugger trains or tow trains):
   The tugger train transports a trailer consisting of a series of wagons for carrying parts, figure 3.23. Compared to the single-load AGV, it has a higher load capacity but also a larger footprint.

Furthermore, material delivery via AGV could be in the form of a "milk-run." The "milk-run" is a method for delivering components with a single tour to drop-off points within various departments. The vehicle is loaded within the material storage area and dispatched to visit the various stations following a specific route to minimize time and optimize material delivery to the various stations.

Figure 3.23: Multi load AGV (Battini et al. 2015)

- *Unit load dispatching*

  An important aspect that has not yet been considered concerns the dynamic behavior of the system. The good dynamic behavior of the system depends on the rules governing the use of the vehicles and the rules according to which the planned missions are executed (Pareschi et al., 2011). To address this issue, a set of traffic management rules, known as dispatching rules, must be defined. These rules are simple and easy to use, and they are employed by the vehicle control system to make decisions regarding which tasks to perform first. They can be divided into two categories (Le Anh & De Koster, 2007, Ho & Chien, 2007):

- Work-centre-initiated rules: Select a vehicle from a set of currently idle vehicles and assign the vehicle to a unit-load pickup task generated at a workstation.
- Vehicle-initiated rules: Select a work centre from a set of work centres simultaneously requesting for the transport service of vehicle. An idel vehicle selects the job that has the highest priority.

Dispatching rules can also be divided into single- and multi-attribute dispatching rules (Le Anh & De Koster, 2007). Single-attribute dispatching rules dispatch vehicles based on only one parameter. Some of these rules are:

- Shorter travel distance first (STDF):

  The AGV calculates the distance between its position and the various stations to which the loaded components need to be delivered. The station to be visited first will be the one with the shortest distance.
- Nearest vehicle first (NVF):

  The order is assigned to the nearest available vehicle to the calling point.
- Longest Idle (LI):

  The order is assigned to the vehicle that has been idle for the longest time.
- Least utilized vehicle (LUV):

  The order is assigned to the least utilized vehicle.

The multi-attribute dispatching rules dispatch vehicles based on a multi-attribute dispatching function, which takes into account several parameters. The decision attributes should be chosen based on their influence on the system's performance. For example, Le-Ahn and De Koster (2007) utilize parameters such as the vehicle empty travel distance and the load waiting time because, in their case study, capacities of queues are not the bottleneck in the system. Therefore, vehicle travel distance and load waiting times primarily affect the system performance. In literature, various dispatching rules, both single and multi-attribute, can be found. However, according to Ahn and De Koster (2007), there is no general dispatching rule that is universally applicable to all cases; instead, they need to be adapted to specific scenarios.

- *Battery recharging*

  Designated zones within the facility are allocated for the recharging of batteries. Within these zones, AGVs have the capability to independently swap out depleted batteries with fully charged ones. Consequently, when the battery level falls below a specified threshold, AGVs must proceed to the designated recharge area to exchange the battery.

3.3.3 Autonomous Mobile Robot (AMR)

With the swift adoption of new practical developments in sensors and robot control technology, advanced AGV systems have gradually come into existence. Eventually, these systems gave rise to a novel category of vehicles known as autonomous mobile robots (AMRs). AMRs are a class of variable path AGVs that utilize a decentralized decision-making method to navigate safely, enabling them to perform tasks such as material handling, collaborative operations, and diverse services within a specified zone without encountering collisions (Pizoń et al. 2024, Frangapane et al. 2021).

The AMRs enable sophisticated functionalities for self-directed operation, encompassing not just navigation and object identification but also object manipulation within unpredictable and changing surroundings. AMRs can engage in various tasks beyond basic transportation and material handling operations, including patrolling and collaborating with operators. The activities they perform, in a manufacturing environment, categorize and differentiate AMRs into two main categories (Frangapane et al., 2021):

1) Covering material handling, such as picking, moving, transporting, and sorting

2) Collaborative and interactive activities

The features of this system have the following attributes (Frangapane et al., 2021; Pizoń et al., 2024):

- Decentralized control: using intelligent, cognitive, and behavior-based control methodologies and technologies to maximize flexibility and efficiency. Unlike AGV systems where a central unit manages control decisions such as routing and dispatching for all vehicles, AMRs can autonomously communicate and negotiate with other resources like machinery and systems such as enterprise resource planning or material handling assessment and control software and make decisions independently, see figure 3.24.
- Platform support: a platform to extend AMR capabilities and enable applications beyond standard material handling operations.
- Collaboration: the ability to work with humans or other AMR robots in a swarm.
- Ease of integration: Quick and cost-effective integration of AMR robots into a factory or other facility.
- Scalability: ability to increase or decrease the number of AMR robots without being hindered by structural changes.
- Robustness: ensuring resilience, i.e., the ability of systems to recover from failure

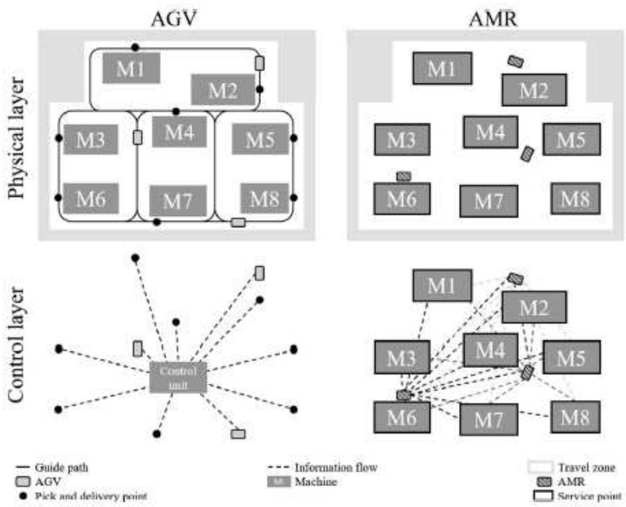


Figure 3.24: Difference in control unit between AGV and AMR (Frangapane et al. 2021)

In this research, the focus will be on the utilization of AMRs in intralogistics, specifically between warehouses and manufacturing systems, which are more traditional sectors where these vehicles are applied. The main activity in which AMRs are employed in intralogistics concerns material handling tasks (figure 3.25). In this context, the vehicles are used to transport materials from storage points to drop-off points within the manufacturing system. They can be equipped with various tools (such as forks or other lifting mechanisms) that enable them to move different loads such as pallets, shelves, or they can be used as tow trains to tow multiple wagons containing parts for delivery.

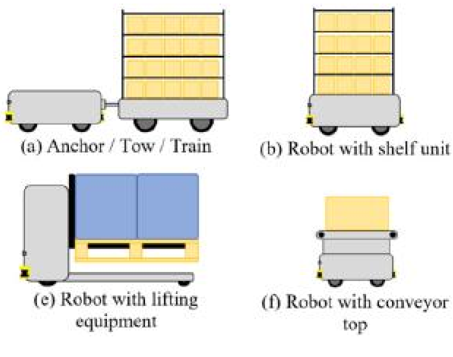


Figure 3.25: Main activity in which AMRs are employed in intralogistics (Frangapane et al. 2021)

3.3.3.1 AMR components

The guidance system that differentiates AMRs from previous versions of automated guided vehicles is a vision-based system, as shown in figure 3.26. AMRs use various systems to understand their operational environment and navigate within facilities without the need to define and implement reference points in advance.

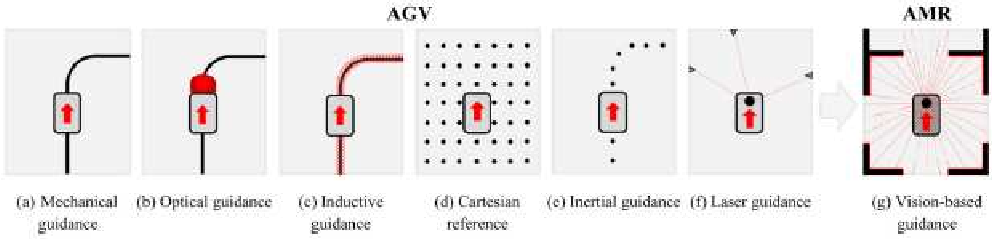


Figure 3.26: Difference in guidance system between AGV and AMR (Frangapane et al. 2021)

The components of the AMR enable the efficient control and design of systems that characterize vision-based guidance. The components of the robot have been grouped and divided into two main categories: the hardware component and the software component. In this section, the characteristics of the vision-based guidance technology will be explored through its components according to the framework shown in figure 3.27.

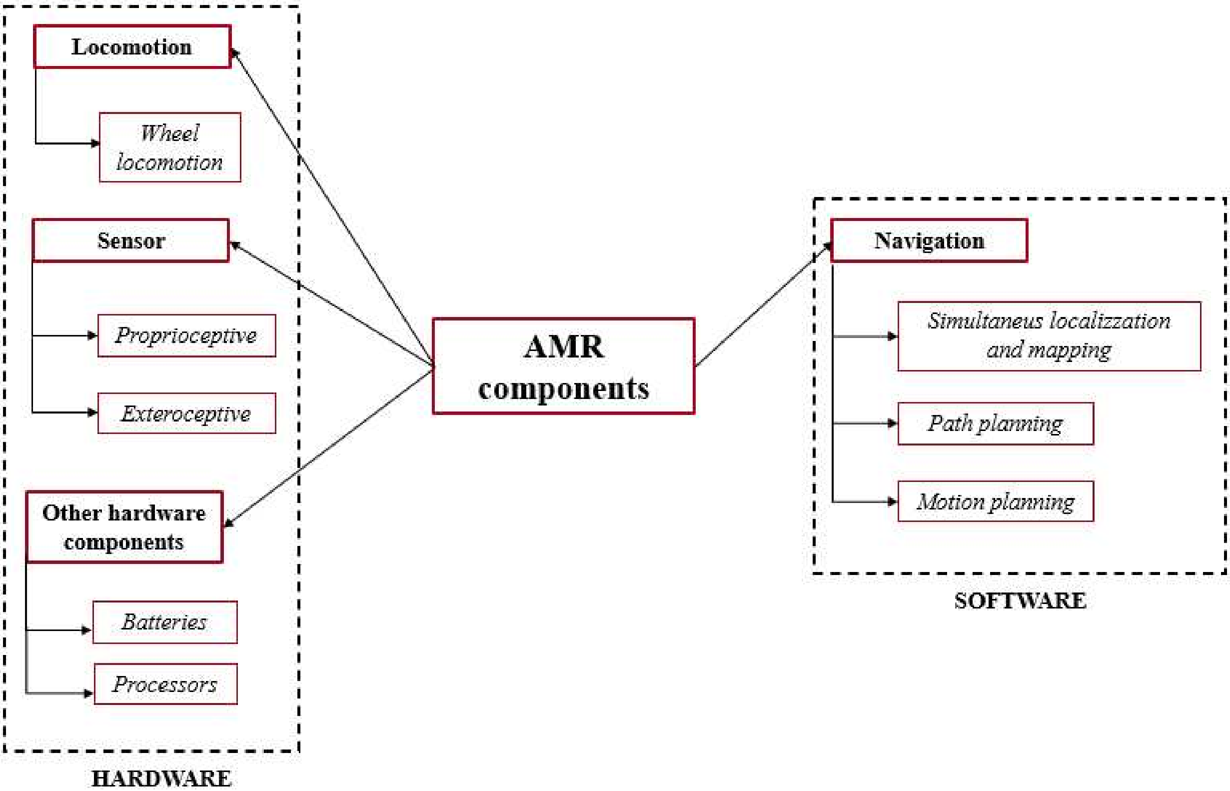


Figure 3.27: Framework of AMR components

3.3.3.1.1 Hardware

The hardware component of the robot consists of sensors, the robot's locomotion mechanism, the battery, and the processor (Frangapane et al., 2021).

3.3.3.1.1.1 Sensor

Sensors detect physical changes in the environment and process them into electrical signals that can then be used by the robot to make various decisions. An AMR consists of several sensors that can be divided into two main areas (Niloy et al., 2021): proprioceptive sensors and exteroceptive sensors.

- *Proprioceptive sensors*

  Proprioceptive sensors are able to read signals coming from internal components of the robot. In an AMR, proprioceptive sensors include:

  - Inertial sensors: Inertial sensors, also known as IMUs (Inertial Measurement Units), are passive sensors, meaning they do not emit any form of energy but detect changes by capturing and measuring variations already present in the environment. This type of sensor is used to measure the acceleration, velocity, and orientation of the robot. In fact, these sensors are a combination of accelerometers, gyroscopes, and sometimes magnetometers. (Altaise and Hancke, 2020)
  - Encoder: They are passive motion sensors. They provide information on wheel positioning and calculate the distance traveled by the robot. They regulate wheel speed and provide feedback for motion control.

- *Exteroceptive sensors*

  Exteroceptive sensors measure signals from the external operational environment of the robot. These include:

  - Distance sensors: There are various types of distance sensors that an AMR can use to calculate the distance from an object or obstacle. These sensors can be either passive or active. An active sensor has its own energy source, which is used to read information from the external environment in some way. Some examples of active distance sensors used in AMRs include LIDAR (Light Detection and Ranging) sensors, ultrasonic sensors, infrared sensors, and RGB-D sensors. In contrast, an example of a passive sensor is optical flow sensors.
  - Force and pressure snesors: They are passive sensors found in AMRs for material handling. Their main function is to measure the forces applied during lifting and handling of loads.

3.2.3.1.1.2 Locomotion mechanism

The most popular locomotion mechanism for AMRs used in intralogistics operations is based on wheel locomotion (Nyloy et al., 2021). This system has become popular because it provides good stability to the robot, makes it easily controllable, and has a simple design that makes it easier to repair compared to other robot locomotion mechanisms. In various intralogistics applications, different types of wheels can be used, such as standard wheels, caster wheels, Swedish wheels, and ball wheels (Nyloy et al., 2021). The key is to provide the robot with the type of wheel that allows it to operate effectively (meaning it enables maneuverability, control, and stability) in the work environment where it is installed.

3.2.3.1.1.3 Others hardware components

- *Batteries*

  Batteries in AMRs provide power to various systems and are crucial for ensuring their autonomy. The development of high-performance batteries, such as lithium-ion batteries, has allowed AMRs to have a more compact design, longer operating times, and greater computing power, enabling their application in tighter spaces and autonomous navigation (Frangapane et al., 2021). Charging methods for batteries range from traditional power sockets with plug-in connectors to wireless energy transfer. The use of wireless charging devices enhances the efficiency of the AMR system because there is no cable wear, thus no maintenance is required, and there are no risks of electric shocks or leaks, ensuring immediate start of charging. (https://digital.phoenixcontact.it/tecnologie-di-ricarica-agv-amr).

- *Processing devicies*

  Processors execute commands and control various subsystems of the AMR. Modern processors based on artificial intelligence such as Intel Nervana, NVIDIA Xavier, and Keron AI SoC provide high computational power that supports these vehicles in operating and navigating in dynamic environments. They enable visual recognition of faces, body gestures, and objects.

3.3.3.1.2 Software

The components belonging to the software part of the robot are based on algorithms primarily used for the autonomous navigation of the AMR. These algorithms generally enable obstacle recognition and avoidance, path optimization, robot localization, and mapping of the surrounding environment.

3.3.3.1.2.1 Navigation

Navigation aspects of AMRs represent critically important challenges for the robot as they enable it to operate and make autonomous decisions within the industrial environment. AMR navigation involves three main aspects: simultaneous localization and mapping, path planning, and motion planning.

- *Simultaneous localization and mapping*
  - Mapping:

    A fundamental issue for AMRs often concerns knowing its current position and understanding the surrounding environment. This dual challenge is addressed with SLAM technology. SLAM (Simultaneous Localization and Mapping) is a navigation support technology for robots that creates detailed maps of the operating environment and calculates the AMR's position (Bloss, 2008; Nyloy et al., 2021). The SLAM approach, based on mapping, allows the robot to navigate smoothly in the industrial environment while performing its tasks. The mapping process converts a 3D point cloud acquired through sensors into a reference map, simultaneously filtering obstacles (Frangapane et al., 2021). There are primarily two types of map representations: metric maps and topological maps, as shown in figure 3.28. In both cases, according to Nyloy et al. (2021), the choice of map should consider that: the map accuracy must meet the robot's desired level, the map features must correspond to those extracted by the sensors, and the map complexity influences the efficiency of robot navigation, mapping, and localization.

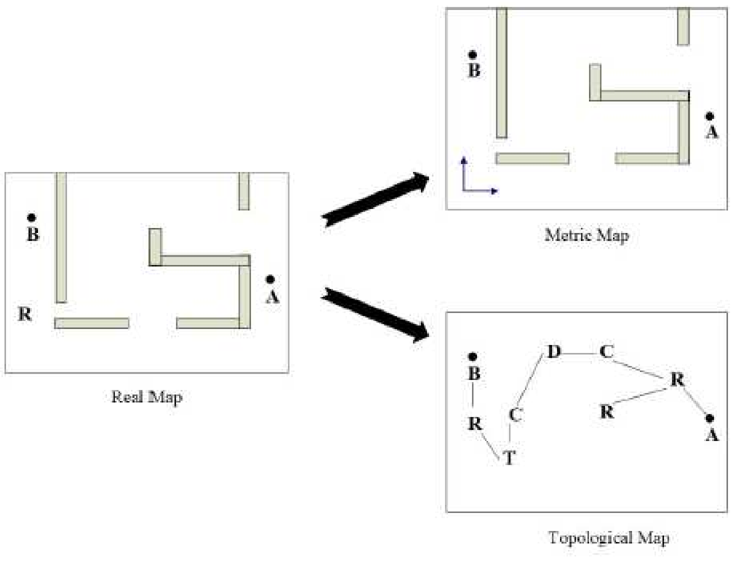


Figure 3.28: Metric map vs Topological map (Nyloy et al., 2021)

- Localization:

  The position of the AMR is calculated by combining information from sensors and other systems (Altatise and Hancke, 2020). Combining sensing information to accurately determine the AMR's position at any time is one of the most challenging problems (Nyloy et al., 2021). Onboard sensors assist the robot in acquiring information about the external environment, but what the sensor detects is not always reliable. The reliability of sensor data is mainly affected by two reasons (Diamantas, 2019): sensor noise and aliasing. Noise is a disturbance in the sensor caused by electromagnetic interference, mechanical vibrations, and environmental conditions (humidity, temperature variations, etc.). Aliasing occurs when a signal is sampled too slowly relative to its frequency, leading to errors in its digital representation. Sensor errors can be minimized using various algorithms. One example is the application of Kalman filtering technology. The Kalman filter uses a recursive algorithm to correct time predictions to estimate the state of a dynamic system and reduce measurement data noise (Frangapane et al., 2021; Nyloy et al., 2021). In practice, combining model predictions of the system and measurements from the real system generates an optimal estimate of the system state over time.

- *Motion planning*

  Motion planning is a fundamental part of the vision-based system and uses inputs from the environment to calculate the dimensions, dynamics of the robot, and a feasible collision-free path. Motion planning operates through motion planning algorithms that provide velocity and steering commands to the vehicle's actuators (such as wheels), determining its movement along the path from the start to the end of its task. In a dynamic environment, motion planning allows the AMR to adjust its speed or stop in front of an obstacle.

- *Path planning*

  Path planning is a crucial task in AMR navigation, where the robot seeks an optimal path based on desired performance outcomes such as shortest time, shortest route, and energy consumption (Longanathan, 2023). Path planning can be divided into two categories based on the type of information from the surrounding environment: global path planning and local path planning (Longanathan, 2023). Global path planning assumes complete knowledge of the surrounding environment. This information is typically provided to the AMR offline, before the robot begins operations. Therefore, strategies associated with global path planning have prior knowledge of the surrounding environment. Among the algorithms used to determine the optimal global path is the A* algorithm, which is employed by the simulation software used to address the case study presented in Chapter 4. On the other hand, local path planning does not have knowledge of the global operational environment and is used by the robot when it is online. Local path planning involves generating an alternative (local) path when an obstacle appears along the global path, as depicted in figure 3.29. In this case, some popular algorithms include Artificial Neural Networks, Fuzzy Logic, and Neuro-Fuzzy Logic (Nyloy et al., 2021)..

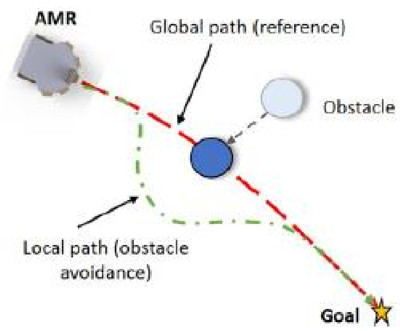


Figure 3.29: Local path for obstacle avoidance (Longanathan, 2023)

3.3.4 Relation between industrial environment and AMR

The AGV system must be built to adapt to the environment in which it operates and to other systems it interacts with; therefore, understanding the AGV's operational environment is essential (Ulrich, 2015). According to Lynch et al. (2018), the navigation system and sensors used by the AGV should be chosen based on the conditions of the operational environment and the tasks the robot needs to perform. Additionally, the layout and conditions of the building heavily influence the choice of navigation technology (Vis et al., 2006). AMR technology is suitable for installation in brownfield facilities, meaning existing industrial structures. Furthermore, the AMR's ability to avoid obstacles and optimize routes makes it suitable for use in dynamic environments.

However, the operational environment poses various challenges to both the hardware and software components of the AMR. The AMR must interact with different systems in the production environment and avoid potential obstacles along its path. Therefore, the proper functioning and efficiency of the AMR also depend on the influence of the operational environment, which tests the robot's components.

This section will investigate the relationship between the working environment and AMRs. Several factors related to the production environment have been identified from literature analysis and will be presented in this section. These factors include layout complexity, working environment, human interaction, vehicle interaction, unit load, floor condition, and network connection, as shown in Figure 3.30.

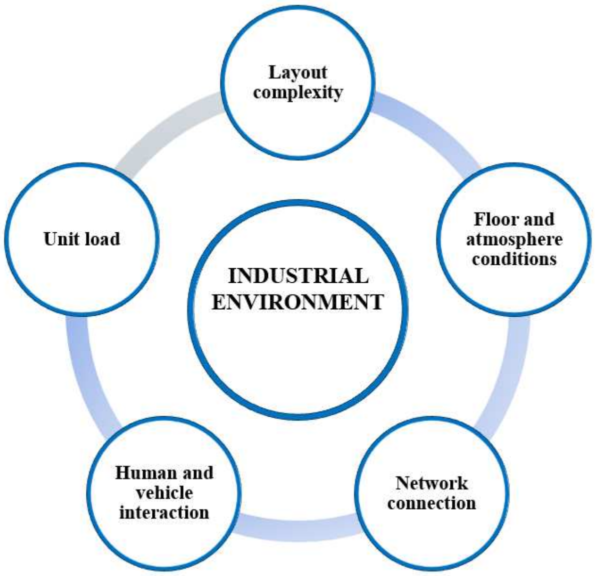


Figure 3.30: Components of industrial environment that effects the operation of AMRs

3.3.4.1 Layout complexity

The layout of the industrial environment refers to the physical arrangement of equipment, machines, workstations, and transport paths. Complex layouts characterized by tight curves and narrow corridors present a challenge for AMR navigation. The configuration of the production system, along with the arrangement of corridors and loading/unloading stations, significantly impacts the efficiency of AMRs. Loading and unloading stations should be strategically positioned to minimize traffic congestion (Pareschi et al., 2011). Meanwhile, corridors must have a minimum width calculated based on the AMR's width (including the load), with an additional 50 cm margin on each side, and if necessary, extra space for opposing traffic (Ulrich, 2015). The width of the corridors should allow for safe maneuvering and loading/unloading by the AMR, avoiding system blockages.

From the site visit, it was observed that maneuvering space for forklift AMRs is a critical and sometimes limited resource. Therefore, corridor width and maneuvering space at loading/unloading points in the layout must be carefully considered.

Another critical aspect of the layout to consider is the peripheral equipment (Ulrich, 2015). As AMRs move between different areas of the production system, they may encounter peripheral equipment such as doors, gates, lifts, and other automatic conveyor systems. These systems should allow the passage of AMRs without causing them to stop or get stuck, ensuring maximum safety. To address this issue, AMRs must be able to communicate directly with these systems to avoid collisions.

These features need careful consideration when introducing AMRs into part feeding processes, as they can restrict movements and maneuvers, leading to inefficiencies in the system. The ability of AMRs to adapt to a dynamic environment makes them more flexible compared to other types of AGVs. However, complex layouts can still pose challenges for the components that make up AMRs. Therefore, understanding the constraints of the production environment layout is crucial for achieving an effective and safe system. Additionally, robust navigation strategies must be provided to AMRs to simultaneously avoid obstacles and create collision-free paths (Longanathan, 2023).

3.3.4.2 Human interaction and vehicle interaction

In intralogistics applications, AGVs share the work environment with operators and other vehicles. The interaction between operators and other vehicles within the production system is a critical aspect of AGV use in intralogistics applications. On one hand, it is essential to maintain a safe working environment for operators and avoid collisions. On the other hand, ensuring a certain level of system efficiency is equally important.

One issue concerning the interaction of AMRs with other vehicles in the production system is congestion. As more vehicles are used in a system, congestion increases (Vis, 2006). Vehicle congestion depends on the number and types of vehicles, as well as throughput (Roy et al., 2012). Decentralizing control of AMR navigation and task allocation can mitigate congestion (Frangapane et al., 2021). They argue that AMR motion planners can adapt to traffic and congestion by adjusting speed or stopping when necessary.

In an AMR, obstacle avoidance is ensured by onboard sensors and obstacle avoidance algorithms (Alatise et al., 2020; Nyloy et al., 2021). The combination of these components enables the robot to process information from the external environment and make autonomous decisions when encountering an obstacle along its path. If a planned path becomes infeasible due to an obstacle, the AMR will generate a new collision-free path.

However, in situations of heavy traffic, the ability of the AMR to avoid obstacles is severely tested, which can lead to reduced performance and system efficiency.

Safety is a critical aspect of AMR interaction with other systems. Recognizing obstacles, avoiding collisions, and implementing safety stops are fundamental requirements for AMRs to ensure a safe environment and must be tested before making the vehicle operational. Additionally, ISO 3691-4 is the standard that establishes safety requirements (European and international) for autonomous guided vehicles. This standard addresses safety protocols and requirements to ensure the safe operation of AGVs considering their autonomous nature. Specifically, to maintain a safe operating area, narrow or "operational danger" areas must be clearly marked with appropriate signage and possibly floor markings (ISO 3691-4).

AMRs can operate safely when these safety measures are considered, and when operators have received adequate training in operating these vehicles.

3.3.4.3 Floor condition and atmosphere conditions

The floor conditions are a critical aspect for AMRs. The criteria for having a floor "suitable for AMRs" generally include (Ulrich, 2015):

- Compressive strength of the pavement: The pavement must withstand the pressure exerted by the robot and the shear forces generated during vehicle maneuvers, acceleration, and deceleration.
- Friction: Friction is crucial for the braking system. Higher friction values can cause excessive wear on the AMR's wheels, while lower values may not ensure effective emergency stopping.
- Flatness of the floor: This is important for the accuracy of load transfers, such as stacking into racks.
- Uphill and downhill part: Uphill sections must be manageable by the vehicle's traction, while downhill sections pose risks during emergency braking.
- Electrical discharge capacity: To prevent electrical shocks, floors should have a maximum ground discharge resistance of 1 MΩ.
- Cleanliness: The floor must be regularly cleaned when operating with AMRs to prevent the system from being affected by dirty surfaces. Additionally, dry floors are necessary to allow the robot to brake safely.

The floor conditions significantly impact AMR technology and can stress both the hardware components (sensors and actuators) and the software components. In fact, during the site visit to the company, it was noted that there were bumps or stains on the floors that needed to be addressed before introducing the two new AMRs. Therefore, it is important to consider these aspects to maintain an adequate level of efficiency and safety in the system.

Another aspect concerning the conditions of the operating environment that needs to be carefully monitored relates to atmospheric conditions (Ulrich, 2015). Critical atmospheric conditions that should be monitored for AMRs operating in enclosed environments include:

- Extreme temperatures: Particularly high or low temperatures (e.g., below 5°C or above 30°C).
- Temperature variations: Rapid changes in temperature.
- High humidity or extremely dry environments: Excessive humidity or very dry conditions.
- Presence of additives in the atmosphere: Such as solvents, water vapor, paint particles, etc.
- High electric or magnetic fields: Which can interfere with AMR's navigation systems.
- Presence of flammable gases: Which pose a safety risk.

The atmospheric conditions in the AMR's working environment should always be monitored closely as deviations from nominal conditions can affect the AMR's localization systems, creating sensor noise (Diamantas, 2019).

3.3.4.4 Network connection

The communication between AMRs and other systems within the production environment occurs through a combination of technologies and communication protocols that enable real-time data exchange, operation coordination, and integration with production systems. To be able to communicate, the microcontroller (mounted on the robot and controlling it) needs to wirelessly communicate with the user via a computer or any other device. Wireless communication can be achieved using: Radio Frequency (RF), Wi-Fi, Global System for Mobile (GSM), ZigBee, or Bluetooth protocols (Khan et al., 2024).

Wi-Fi is a widely adopted wireless communication method used by companies to implement AMRs because it is already present in the company and is also used for other systems. However, as Wi-Fi networks become congested due to heavy usage, the real-time functionality of AMRs may be affected. Some users encounter challenges with Wi-Fi such as (https://www.therobotreport.com/how-5g-connectivity-can-enhance-amrs/):

- Limited/spotty coverage
- Undependable handoffs between access points
- Declining bandwidth
- Unpredictable latency

It is important to note that a small fleet of AMRs can operate effectively using Wi-Fi. However, any increase in fleet size or functionality typically requires a dedicated network solution. (https://www.therobotreport.com/how-5g-connectivity-can-enhance-amrs/).

3.3.4.5 Unit load

The AMRs used in intralogistics operations transport unit loads from one station to another according to the internal flow of materials. Unit loads can vary in type (pallets, containers, boxes, etc.), and when introducing an AMR into an existing layout, it must be equipped with systems that allow it to effectively move the load. During the site visit, two new forklift AMRs were observed to have been introduced. These forklift AMRs were selected to handle unit loads corresponding to pallets measuring 1200 x 800 mm. The company plans to use these AMRs to move floor-to-floor loads from one fixed station to another.

To pick up the load with the AMR, precise positioning within the pickup area is crucial. Failure to meet this requirement prevents the AMR from picking up and completing the load transfer. Besides load positioning, consideration must also be given to the dimensions of the unit load, as observed during the site visit. The dimensions of the unit load can obstruct certain sensors of the AMR, causing the vehicle to stop and requiring operator intervention. In the company visit, the unit loads were wider than the pallets and protruded beyond the load, potentially causing issues with the AMR sensors.

Another critical aspect concerns the variation in unit load designs (Thylén et al., 2024). When an AMR must transport different types of loads, such as various types of pallets, additional requirements are necessary to ensure the proper transfer of the unit load. Therefore, it is essential to make appropriate decisions and equip unit loads with suitable designs to ensure they are detected and handled correctly by the AMR (Thylén et al., 2024).

From these observations, it is evident that considering load compatibility is crucial when utilizing AMRs for material transport, as it can significantly impact operational performance.

4. CASE STUDY

The case study consists of the use of data from a Swedish company to calculate the number of vehicles (AGV) necessary to satisfy the internal transport requests for materials and the use of simulation software (FlexSim) to simulate two scenarios relating to the internal transport of materials. FlexSim is 3D simulation software that models, simulates, predicts, and visualizes business systems in a variety of industries (FlexSim). The first scenario (scenario 1) consists of simulating the transport of materials with only traditional vehicles while the second scenario (scenario 2) represents a completely automated solution or through the use of AMRs only.

The objective of this chapter is to compare the two scenarios and draw information to answer the second research question. The data coming from the company is: a CAD file of the plant and an Excel file containing information relating to material handling requests for each loading or unloading station. The data were used as input to calculate the optimal number of vehicles (AGV) and to build the simulation model as will be seen in the following sections.

4.1 Design of AGV system

This section will address the steps to calculate the optimal number of vehicles needed to serve all the stations of the company's plant and satisfy all the station transportation requests. The data used to size the AGV fleet comes from both the CAD file and the Excel file provided by the company. The steps for designing an AGV system have been divided into two sections which will be explored in depth later. These are: Layout and flow analysis and calculation of the number of AGV.

4.1.1 Layout and flow analysis

The first step to size the AGV fleet is to know the layout of the plant and therefore the position of the AGV loading, unloading and waiting stations. The layout was obtained from a CAD file containing all the information on the dimensions of the plant and the positions of the AGV loading and unloading stations. The production area measures 7751 m^2 and contains 24 stations while the storage area measures 2597 m^2 and contains 2 stations. The total area in which the AGVs move along the corridors measures 10348 m^2, while there are a total of 26 stations to visit, figure 4.1.

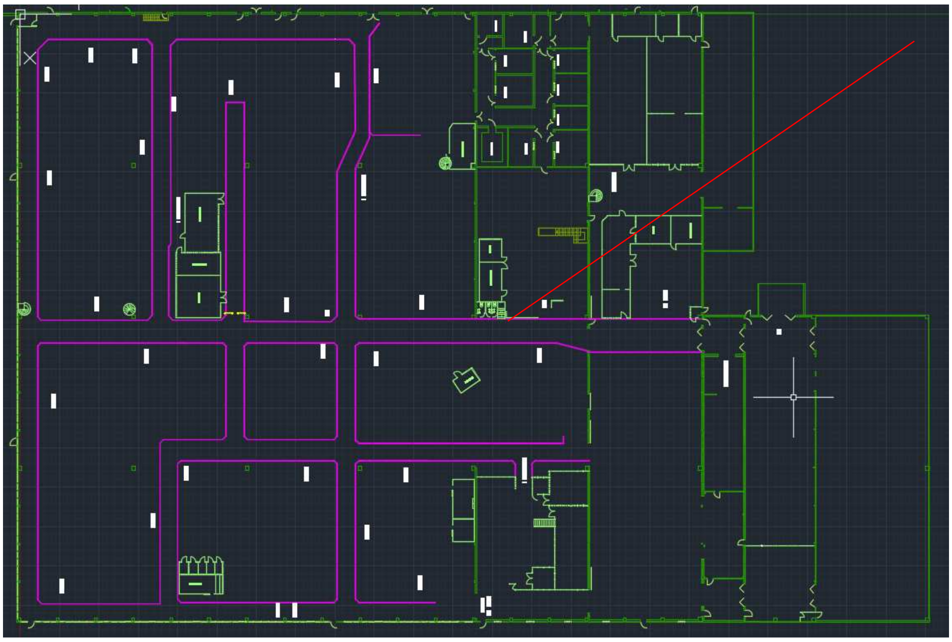


Figure 4.1: CAD of the production and storage area. The white rectangular are the station to be visited. The area sign by the red line is not a part of the production or storage area.

To ensure effective AGV route planning, it is important to consider the placement of pick-up and drop-off stations, the overall factory floor layout and material flow.

The layout analysis includes evaluating the overall layout of the factory floor to verify the space available for AGV routes and the location of pick-up and drop-off stations. This information is important to calculate the theoretical total travel distance of the AGVs which represents a key aspect for calculating the number of AGVs and for optimizing the system.

The analysis of the flow of materials follows that of the layout and is used to understand the flow of materials between the various stations within the plant. This means considering the transport requests for each station taking into account the time required to handle the material. The purpose of the analysis is to understand the dynamics of material flow which is fundamental to determining the requirements of AGVs. First of all, it should be noted that the company works on two 8-hour work shifts, therefore the data relating to the transport of materials that will be analyzed later refer to a 16-hour work shift. It should also be noted that transport requests are created by scanning a barcode and subsequently sent to a work order list in the company ERP. At this point, to determine the flow of materials, the data provided by the company relating to internal transport orders were used. The internal transport orders were divided into ranges and for each range the number of transport days were identified according to table 4.1

Intervallo ordini	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	Giorni	Max richieste
giorni	51	6	16	34	34	45	57	45	14	3	305	93

Table 4.1: number of transport days for each ranges of orders

In particular, the day with the highest number of transport orders was identified within the year 2022. On the basis of this day, the flow of materials for each station of the plant was obtained. In this way it was possible, as will be seen in the next section, to calculate the number of AGVs based on the most critical day, i.e. the one with the greatest number of transport requests. At this point it is possible to build the material flow table. This table is known as from to chart and presents on the rows the stations from which the vehicles depart (from) and on the columns the stations they arrive at (to). In the row-column intersection there is the number of transports that must depart from one station and arrive at another. The from to chart of transports relating to the day in 2022 with the highest number of material movements is represented in table 4.2.

FROM/TO	Miljöstation 3	Oljeboden	T10101	T11101	T11102	T20101	T20102	T20201	T21101	T22103	TOTALE
Miljöstation 3	X										
Oljeboden		X									
T10101			X								
T11101				X							
T11102					X						
T20101						X					
T20102							X				
T20201								X			
T21101									X		
T22103										X	
T22104											
T22105											
T23101											
T23102											
T23103											
T23104											
T27101											
T30101											
T30201											
T30202											
T34101											
T35101											
T72301											
T90101											
Goods ut											
VF			1	3	2	3		4			13
TOTALE			1	3	2	3		4			

FROM/TO	T22104	T22105	T23101	T23102	T23103	T23104	T27101	T30101	TOTALE
Miljöstation 3									
Oljeboden			1						1
T10101									
T11101									
T11102									
T20101									
T20102									
T20201									
T21101									
T22103									
T22104	X								
T22105		X							
T23101			X						
T23102				X					
T23103					X				
T23104						X			
T27101							X		
T30101								X	
T30201									
T30202									
T34101									
T35101									
T72301									
T90101									
Goods ut									
VF	1		3	5	6	1		1	17
TOTALE	1		4	5	6	1		1	

FROM/TO	T30201	T30202	T34101	T35101	T72301	T90101	Goods ut	VF	TOTALE
Miljöstation 3									
Oljeboden									
T10101						17		5	22
T11101								2	2
T11102									
T20101								5	5
T20102									
T20201								5	5
T21101								1	1
T22103								5	5
T22104								1	1
T22105								1	1
T23101									
T23102								4	4
T23103									
T23104								2	2
T27101									
T30101							3		3
T30201	X								
T30202		X						6	6
T34101			X						
T35101				X				3	3
T72301					X			1	1
T90101						X			
Goods ut							X		
VF				1				X	1
TOTALE				1		17	3	41	93

Table 4.2: From to chart of the material flow relating to the day in 2022 with the highest number of transports

4.1.2 Calculation of the number of AGV

To calculate the theoretical number of AGVs it is necessary to obtain two other tables which can be obtained from the data coming from the layout analysis and the material flow analysis. These two tables are: the distance table and the total travel time table loaded with the vehicle.

To build the distance tables, note the from to chart of the flow of materials, I can calculate the distances between the stations where the material is moved. These distances were calculated from the plant's CAD file considering the shortest distances between the stations or considering the bidirectional corridors. In fact, the AGV knows the position of the final transport station and calculates the shortest distance between the two stations. The distances between stations are represented in a table known as the from to distance chart. The table 4.3, like the from to chart of the flow of materials, represents the stations from which the vehicle leaves on the rows and the stations at which it arrives on the columns. In this case in the row-column intersection there are the distances in meters (m) between the stations.

Subsequently, once the from to distance chart was known, the table of the total travel time loaded with the vehicle was constructed. To calculate these times it is necessary to know the speed of the vehicle which is a maximum of 1.4 m/s but on average 0.7 m/s was used. Furthermore, in addition to the standard times, i.e. those obtained by dividing the distances between the stations by the average speed of the vehicle, additional times relating to: Add for peak load, add for layout doors and changing time were considered. These data are represented in table 4.3.

Add for Peak load	Add for layout/ doors	Chargin g time	Average speed (max. 1.4m/s)
%	**%**	**%**	(max. 1.4m/s)
10%	10%	7%	0,7

Table 4.3: Additional time for AGV and average speed

Once these parameters are known, it is possible to obtain the table of the total loaded travel time of the vehicle known as the loaded travel time from to chart. This table is constructed like the previous ones, that is, it presents the stations on the rows and columns while the loaded travel time of the vehicle is calculated at the row/column intersection. This loaded travel time is calculated by dividing the distances between one station and another by the average speed of the AGV and adding the additional times represented in table 4.3, according to the following expression:

$$T_{tot,load} = \left(\frac{\sum d_{ij}}{Avarege\ speed}\right) * (Add\ for\ peak\ load + add\ for\ layout/doors + changing\ time)$$

Where d_{ij} is the distance between station i and station j. The movement between two stations is optimized by selecting the route with the shortest travel time. The from to chart of the travel times loaded with the vehicle is represented in table 4.4

FROM/TO Distance [m]	Miljöstation 3	Oljeboden	T10101	T11101	T11102	T20101	T20102	T20201	T21101	T22103
Miljöstation 3	X									
Oljeboden		X								
T10101			X							
T11101				X						
T11102					X					
T20101						X				
T20102							X			
T20201								X		
T21101									X	
T22103										X
T22104										
T22105										
T23101										
T23102										
T23103										
T23104										
T27101										
T30101										
T30201										
T30202										
T34101										
T35101										
T72301										
T90101										
Goods ut										
VF			37	79	122	124		100		

FROM/TO Distance [m]	T22104	T22105	T23101	T23102	T23103	T23104	T27101	T30101
Miljöstation 3								
Oljeboden			121					
T10101								
T11101								
T11102								
T20101								
T20102								
T20201								
T21101								
T22103								
T22104	X							
T22105		X						
T23101			X					
T23102				X				
T23103					X			
T23104						X		
T27101							X	
T30101								X
T30201								
T30202								
T34101								
T35101								
T72301								
T90101								
Goods ut								
VF	128		131	110	102	160		114

FROM/TO Distance [m]	T30201	T30202	T34101	T35101	T72301	T90101	Goods ut	VF
Miljöstation 3								
Oljeboden								
T10101						97		37
T11101								79
T11102								
T20101								123
T20102								
T20201								119
T21101								114
T22103								160
T22104								132
T22105								142
T23101								
T23102								110
T23103								
T23104								160
T27101								
T30101							71	
T30201	X							
T30202		X						126
T34101			X					
T35101				X				58
T72301					X			73
T90101						X		
Goods ut							X	
VF				58				X

Table 4.4: From to chart of the distances between the various stations that require the transport of material

FROM/TO of time load trips [s]	Miljöstation 3	Oljeboden	T10101	T11101	T11102	T20101	T20102	T20201	T21101	T22103
Miljöstation 3	X									
Oljeboden		X								
T10101			X							
T11101				X						
T11102					X					
T20101						X				
T20102							X			
T20201								X		
T21101									X	
T22103										X
T22104										
T22105										
T23101										
T23102										
T23103										
T23104										
T27101										
T30101										
T30201										
T30202										
T34101										
T35101										
T72301										
T90101										
GOODS UT										
VF			67	143	221	225		181		

FROM/TO of time load trips [s]	T22104	T22105	T23101	T23102	T23103	T23104	T27101	T30101
Miljöstation 3								
Oljeboden			220					
T10101								
T11101								
T11102								
T20101								
T20102								
T20201								
T21101								
T22103								
T22104	X							
T22105		X						
T23101			X					
T23102				X				
T23103					X			
T23104						X		
T27101							X	
T30101								X
T30201								
T30202								
T34101								
T35101								
T72301								
T90101								
GOODS UT								
VF	232		238	200	185	290		207

FROM/TO of time load trips [s]	T30201	T30202	T34101	T35101	T72301	T90101	GOODS UT	VF
Miljöstation 3								
Oljeboden								
T10101						176		67
T11101								143
T11102								
T20101								223
T20102								
T20201								216
T21101								207
T22103								290
T22104								239
T22105								258
T23101								
T23102								200
T23103								
T23104								290
T27101								
T30101							220	
T30201	X							
T30202		X						229
T34101			X					
T35101				X				105
T72301					X			132
T90101						X		
GOODS UT							X	
VF				105				X

Table 4.5: From to chart of the total travel times loaded with the AGV calculated in [s]

Let's define:

$\sum_j n_{ij}$ = number of vehicles required at the i-th station to move the material during the shift

$\sum_i n_{ij}$ = number of vehicles arriving at the j-th station during the shift

The total time for transport activities during the shift is:

$$H' = \sum_i \sum_j n_{ij} \cdot T_{tot,load}$$

It should be noted that at the beginning and end of each shift, there will be a certain number of rebalancing empty trips to return the system to its initial conditions and prepare it for the next shift's production. Therefore, an increase in travel time due to loading, unloading, waiting, and rebalancing times is established, denoted as ΔH. To determine ΔH, we need to calculate the net flows of vehicles for each station. The net flow of AGV, NF(i), at the i-th station is given by:

$$NF(i) = -\sum_i n_{ij} + \sum_j n_{ij} + f_i - g_i$$

Where:

$-\sum_i n_{ij}$ = Outgoing flow from i to satisfy stations j

$\sum_j n_{ij}$= Incoming flow to i from stations j

f_i = Vehicles available at "i" at the beginning of the shift

g_i = Vehicles required at station "i" at the end of the shift

It must be as much as possible:

$$\sum_i NF(i) = 0$$

To optimize the vehicle allocation, when there's a surplus of vehicles at station i, indicated by NF(i) > 0, and there's a need to fulfill other stations j with NF(j) < 0, it's essential to redistribute the vehicles strategically. This redistribution ensures efficient utilization of resources and meets the demands of the entire system. The table 4.5 illustrate the net flow of AGV, NF(i), for each station

[trips/day]	Oljeboden	T10101	T11101	T11102	T20101	T20201	T21101	T22103	T22104	T22105	T23101
To		1	3	2	3	4		1		4	5
From	-1	-22	-2		-5	-5	-1	-5	-1	-1	
NF(i)	**-1**	**-21**	**1**	**2**	**-2**	**-1**	**-1**	**-4**	**-1**	**3**	**5**

[trips/day]	T23102	T23103	T23104	T27101	T30101	T30202	T34101	T35101	T72301	T90101	VF
To	6	1		1			1		17	3	41
From	-4		-2		-3	-6		-3	-1		-31
NF(i)	**2**	**1**	**-2**	**1**	**-3**	**-6**	**1**	**-3**	**16**	**3**	**10**

Table 4.5: Net flow for each station of the system

Let:

- x_{ij} = the number of empty trips that should be made from station "i" to station "j" per vehicle during the shift for rebalancing purposes.
- t_{ij} = Shortest path time from "i" to "j" when the vehicle is empty.

The total time of empty trips along the routes is expressed by:

$$\Delta H = \sum_i \sum_j x_{ij} \cdot t_{ij} = 4784 \ [\frac{s}{day}]$$

The table 4.6 illustrate the value of x_{ij}, t_{ij}, and ΔH of empty trips for the day of the maximum transport request.

From	Oljeboden	T10101	T10101	T10101	T23104	T35101	T20101	T20201	T21101	T22104	T30101	T22103	T30202
To	T11101	T11102	T22105	T72301	T23101	T23101	T23102	T23103	T27101	T34101	T90101	VF	VF
Empty trips, Xij	1	2	3	16	2	3	2	1	1	1	3	4	6
Distance (m)	72	84	106	33	37	73	116	58	56,5	58	71	158	120
Time, tij [s]	103	120	151	47	53	104	166	83	81	83	101	226	171
ΔH	103	240	454	754	106	313	331	83	81	83	304	903	1029

Table 4.6: Value of x_{ij}, t_{ij}, and ΔH of empty trips

At this point, I know the overall travel time of the AMR:

$$H = \sum_i \sum_j n_{ij} \cdot t''_{ij} + \Delta\mathrm{H}$$

In our case $H = 22821{,}2\ [\frac{s}{day}]$. Therefore, the minimum number of AGVs it is calculated as the ratio between the calculated overall time and the reference duration (1 shift = 16 h). Given the availability hours of an AMR cart in one shift, calculated as the vehicle's efficiency η per 3600, the minimum number of AMR Y is obtained:

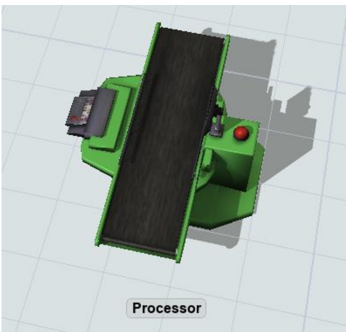
$$\frac{H}{(\eta * 16 * 3600)} = X \rightarrow \lceil X \rceil = Y = 1$$

With $\eta = performance = 0{,}90$

The number of AMR equal to 1 is due to the fact that the transport requests between stations (n_{ij}) are low frequency. This significantly influences the overall travel time of the AMR (H) on which the calculation of the theoretical number of AMR depends.

4.2 Construction of the simulation model

The simulation model is built with Flexsim software. Through Flexsim it is possible to represent each of the stations through the composition of 3D objects. To do this, two objects were dragged into the model from the software's object library to represent each of the 26 stations. These two objects are: the Processor and Queue, figure 4.2. The processor is used to simulate the processing of flow items in a model instead the queue is used to store flow items (Flexsim). Therefore in our case the processor represents the line or the machinery while the queue represents a buffer in which the materials are stored.



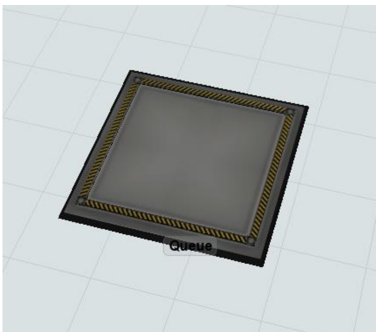


Figure 4.2: Processor and Queue from Flexsim software

To respect the dimensions and layout of the production and storage areas as much as possible, the CAD file of the plant was imported into Flexsim. The two objects (processor and queue) were positioned in the model respecting the layout of the stations in the CAD. The model thus constructed is represented in the figure 4.3.

Figure 4.3: Representation of the simulating model in flexsim environment

Furthermore, to ensure that vehicles do not pass through the production areas but travel along the designated corridors, these areas have been limited through control areas, in figure X in gray.

At this point, having positioned the objects (processor and queue) and defined the corridors through the use of control areas, the processors must be set with the data relating to the transport requests provided by the company. The data relating to transport requests are for the year 2022 and include almost all the stations of the plant that will be served by the AMR. Table 4.7 represents the flow of materials via the from to chart.

FROM/TO	Miljöstation	Oljeboden	T10101	T11101	T11102	T20101	**T20102**	T20201	T21101	T22103	T22104	T22105	T23101	T23102	T23103	T23104	T27101	T30101	T30201	T30202	T34101	T35101	T72301	T90101	Goods ut	VF	TOTALE
Miljöstation 3	X																									4	**4**
Oljeboden		X				18		1	10	15	2		5	4	3	14	16	9		10	2	8					**117**
T10101			X																					2156		506	**2662**
T11101				X																						305	**305**
T11102					X																					55	**55**
T20101						X																				20	**20**
T20102							X																			1076	**1076**
T20201								X																		562	**562**
T21101		9							X																	96	**105**
T22103										X																710	**710**
T22104		17									X															59	**76**
T22105												X														139	**139**
T23101		6											X													109	**115**
T23102		9												X												367	**376**
T23103		2													X										79	110	**191**
T23104		8														X										303	**311**
T27101																	X									78	**78**
T30101		11																X							623	448	**1082**
T30201																			X						3	24	**27**
T30202		4																		X						805	**809**
T34101		3																			X					107	**110**
T35101		7																				X				649	**656**
T72301																							X			270	**270**
T90101																								X			**0**
Goods ut																									X		**0**
VF			144	283	55	269		477	1		204		214	175	122	139	142	893			45	655				X	**3818**
TOTALE		**76**	**144**	**283**	**55**	**287**		**478**	**11**	**15**	**206**		**219**	**179**	**125**	**153**	**158**	**902**		**10**	**47**	**663**		**2156**	**705**	**6802**	**13674**

Table 4.7: From to chart of 2022 transport flows

To set up the simulation processors you need to run the analysis on the transportation data for each station. The analysis was carried out through Minitab which is a statistical analysis software. With Minitab we analyzed the transport request deltas for each station, in seconds, between one order and the previous one. To identify this data it was first necessary to build an Excel table. The excel table was constructed in the following way, example table 4.8:

- From location: Contains the name of the departure station.
- To location: Contains the name of the arrival station. In this case the station called T27101 was taken as an example in which the materials must be moved only to the station called VF (in general the movement of the material from a station can also involve multiple stations, but for simplicity in the complete representation of the table it was decided to represent this station).
- Mission created [day]: Contains the date where the transport mission was created
- Mission completed [day]: Contains the date where the transport mission was finished
- Mission created [time]: Contains the time where the transport mission was created Colonna3: it is a support column in which the hours 06:00:00 are displayed at the beginning of each day. For days with multiple freight orders, a 0 appears after the first order
- Delta: The deltas, in hours, between one transport order and the previous one are calculated. For the first order the difference is between the request time and the shift start time which is always 06:00:00
- Delta [s]: Contains the value of the previously calculated deltas but in seconds. It is the final result of the analysis in excel.

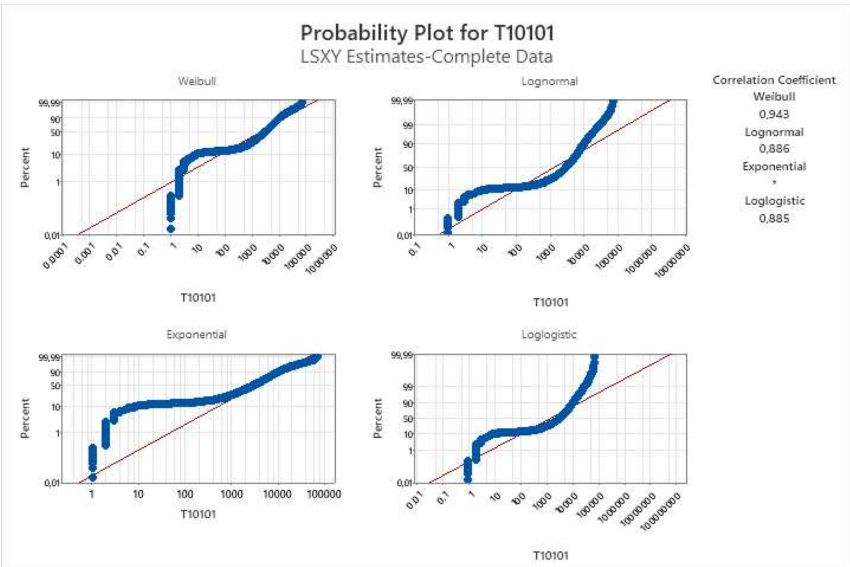
From location	To location	Mission created[DAY]	Mission completed [DAY]	Year	Mission created [TIME]	Colonna3	Delta	Delta [s]
T27101	VF	05/01/2022	05/01/2022	2022	12:16:54	06:00:00	06:16:54	**22614,00**
T27101	VF	19/01/2022	19/01/2022	2022	14:58:41	06:00:00	08:58:41	**32321,00**
T27101	VF	20/01/2022	20/01/2022	2022	19:39:28	06:00:00	13:39:28	**49168,00**
T27101	VF	26/01/2022	26/01/2022	2022	13:44:37	06:00:00	07:44:37	**27877,00**
T27101	VF	28/01/2022	28/01/2022	2022	12:31:29	06:00:00	06:31:29	**23489,00**
T27101	VF	02/02/2022	02/02/2022	2022	10:06:23	06:00:00	04:06:23	**14783,00**
T27101	VF	08/02/2022	08/02/2022	2022	06:10:07	06:00:00	00:10:07	**607,00**
T27101	VF	11/02/2022	11/02/2022	2022	11:57:07	06:00:00	05:57:07	**21427,00**
T27101	VF	14/02/2022	14/02/2022	2022	13:21:30	06:00:00	07:21:30	**26490,00**
T27101	VF	17/02/2022	17/02/2022	2022	14:16:02	06:00:00	08:16:02	**29762,00**
T27101	VF	18/02/2022	18/02/2022	2022	11:44:11	06:00:00	05:44:11	**20651,00**
T27101	VF	25/02/2022	25/02/2022	2022	06:44:02	06:00:00	00:44:02	**2642,00**
T27101	VF	25/02/2022	25/02/2022	2022	06:44:48	0	00:00:46	**46,00**
T27101	VF	03/03/2022	03/03/2022	2022	14:55:06	06:00:00	08:55:06	**32106,00**
T27101	VF	09/03/2022	09/03/2022	2022	06:43:41	06:00:00	00:43:41	**2621,00**
T27101	VF	11/03/2022	11/03/2022	2022	10:53:48	06:00:00	04:53:48	**17628,00**
T27101	VF	17/03/2022	17/03/2022	2022	12:52:08	06:00:00	06:52:08	**24728,00**
T27101	VF	17/03/2022	17/03/2022	2022	14:48:12	0	01:56:04	**6964,00**
T27101	VF	17/03/2022	17/03/2022	2022	18:14:26	0	03:26:14	**12374,00**
T27101	VF	29/03/2022	29/03/2022	2022	20:44:18	06:00:00	14:44:18	**53058,00**
T27101	VF	07/04/2022	07/04/2022	2022	10:53:39	06:00:00	04:53:39	**17619,00**
T27101	VF	08/04/2022	08/04/2022	2022	09:43:36	06:00:00	03:43:36	**13416,00**
T27101	VF	19/04/2022	19/04/2022	2022	12:45:07	06:00:00	06:45:07	**24307,00**
T27101	VF	21/04/2022	21/04/2022	2022	07:24:12	06:00:00	01:24:12	**5052,00**
T27101	VF	27/04/2022	27/04/2022	2022	10:40:40	06:00:00	04:40:40	**16840,00**
T27101	VF	28/04/2022	28/04/2022	2022	15:39:47	06:00:00	09:39:47	**34787,00**
T27101	VF	06/05/2022	06/05/2022	2022	11:01:33	06:00:00	05:01:33	**18093,00**
T27101	VF	13/05/2022	13/05/2022	2022	07:01:26	06:00:00	01:01:26	**3686,00**
T27101	VF	20/05/2022	20/05/2022	2022	10:17:31	06:00:00	04:17:31	**15451,00**
T27101	VF	01/06/2022	01/06/2022	2022	06:53:17	06:00:00	00:53:17	**3197,00**
T27101	VF	08/06/2022	08/06/2022	2022	19:26:20	06:00:00	13:26:20	**48380,00**
T27101	VF	20/06/2022	20/06/2022	2022	09:57:18	06:00:00	03:57:18	**14238,00**
T27101	VF	22/06/2022	22/06/2022	2022	12:54:06	06:00:00	06:54:06	**24846,00**
T27101	VF	27/06/2022	27/06/2022	2022	09:55:47	06:00:00	03:55:47	**14147,00**
T27101	VF	05/07/2022	05/07/2022	2022	18:02:53	06:00:00	12:02:53	**43373,00**
T27101	VF	13/07/2022	13/07/2022	2022	08:57:07	06:00:00	02:57:07	**10627,00**
T27101	VF	14/07/2022	14/07/2022	2022	13:39:38	06:00:00	07:39:38	**27578,00**
T27101	VF	27/07/2022	27/07/2022	2022	10:42:52	06:00:00	04:42:52	**16972,00**
T27101	VF	02/08/2022	02/08/2022	2022	13:42:55	06:00:00	07:42:55	**27775,00**
T27101	VF	09/08/2022	09/08/2022	2022	14:13:29	06:00:00	08:13:29	**29609,00**
T27101	VF	10/08/2022	10/08/2022	2022	06:33:40	06:00:00	00:33:40	**2020,00**
T27101	VF	10/08/2022	10/08/2022	2022	13:49:58	0	07:16:18	**26178,00**
T27101	VF	16/08/2022	16/08/2022	2022	20:44:47	06:00:00	14:44:47	**53087,00**
T27101	VF	17/08/2022	17/08/2022	2022	16:38:11	06:00:00	10:38:11	**38291,00**
T27101	VF	22/08/2022	22/08/2022	2022	10:05:48	06:00:00	04:05:48	**14748,00**
T27101	VF	25/08/2022	25/08/2022	2022	07:04:09	06:00:00	01:04:09	**3849,00**
T27101	VF	06/09/2022	06/09/2022	2022	07:05:44	06:00:00	01:05:44	**3944,00**
T27101	VF	12/09/2022	12/09/2022	2022	13:01:48	06:00:00	07:01:48	**25308,00**
T27101	VF	21/09/2022	21/09/2022	2022	22:25:20	06:00:00	16:25:20	**59120,00**
T27101	VF	26/09/2022	26/09/2022	2022	15:45:37	06:00:00	09:45:37	**35137,00**
T27101	VF	30/09/2022	30/09/2022	2022	07:56:33	06:00:00	01:56:33	**6993,00**
T27101	VF	03/10/2022	03/10/2022	2022	07:04:13	06:00:00	01:04:13	**3853,00**
T27101	VF	10/10/2022	10/10/2022	2022	18:35:53	06:00:00	12:35:53	**45353,00**
T27101	VF	10/10/2022	10/10/2022	2022	18:36:34	0	00:00:41	**41,00**
T27101	VF	19/10/2022	19/10/2022	2022	09:24:16	06:00:00	03:24:16	**12256,00**
T27101	VF	19/10/2022	19/10/2022	2022	21:42:10	0	12:17:54	**44274,00**
T27101	VF	19/10/2022	19/10/2022	2022	21:42:20	0	00:00:10	**10,00**
T27101	VF	27/10/2022	27/10/2022	2022	20:52:30	06:00:00	14:52:30	**53550,00**
T27101	VF	03/11/2022	03/11/2022	2022	13:03:06	06:00:00	07:03:06	**25386,00**
T27101	VF	09/11/2022	09/11/2022	2022	10:11:10	06:00:00	04:11:10	**15070,00**
T27101	VF	09/11/2022	09/11/2022	2022	15:23:06	0	05:11:56	**18716,00**
T27101	VF	11/11/2022	11/11/2022	2022	07:36:31	06:00:00	01:36:31	**5791,00**
T27101	VF	16/11/2022	16/11/2022	2022	08:45:46	06:00:00	02:45:46	**9946,00**
T27101	VF	18/11/2022	18/11/2022	2022	12:44:21	06:00:00	06:44:21	**24261,00**
T27101	VF	22/11/2022	22/11/2022	2022	11:38:52	06:00:00	05:38:52	**20332,00**
T27101	VF	22/11/2022	22/11/2022	2022	22:05:04	0	10:26:12	**37572,00**
T27101	VF	24/11/2022	24/11/2022	2022	10:12:13	06:00:00	04:12:13	**15133,00**
T27101	VF	28/11/2022	28/11/2022	2022	06:11:48	06:00:00	00:11:48	**708,00**
T27101	VF	28/11/2022	28/11/2022	2022	17:43:43	0	11:31:55	**41515,00**
T27101	VF	28/11/2022	28/11/2022	2022	17:43:52	0	00:00:09	**9,00**
T27101	VF	01/12/2022	01/12/2022	2022	07:41:25	06:00:00	01:41:25	**6085,00**
T27101	VF	02/12/2022	02/12/2022	2022	09:56:43	06:00:00	03:56:43	**14203,00**
T27101	VF	05/12/2022	05/12/2022	2022	18:26:05	06:00:00	12:26:05	**44765,00**
T27101	VF	08/12/2022	08/12/2022	2022	11:57:07	06:00:00	05:57:07	**21427,00**
T27101	VF	15/12/2022	15/12/2022	2022	10:41:02	06:00:00	04:41:02	**16862,00**
T27101	VF	21/12/2022	21/12/2022	2022	11:45:48	06:00:00	05:45:48	**20748,00**
T27101	VF	21/12/2022	21/12/2022	2022	18:52:25	0	07:06:37	**25597,00**
T27101	VF	29/12/2022	29/12/2022	2022	07:13:11	06:00:00	01:13:11	**4391,00**

Table 4.8: Excel table for the analysis of the delta request of transport for T27101 station.

Once the delta in seconds was calculated for each station, this data was imported into Minitab for the statistical analysis which was carried out as follows:

1. **Distribution ID Plot**: To identify the distribution of the data, a distribution search analysis is first performed. To do this, launch a distribution analysis-right censoring and then distribution ID plot in minitab. Right-censoring allows you to analyze the deltas between one order and the previous one considering the data relating to 2022. The data will then be recorded as "censored" to 2022, indicating that the observation was stopped at that point. We proceed by inserting all the distributions into the analysis by selecting the "use all distribution" option and the least square estimation method option. The least squares method minimizes the sum of the squares of the differences (errors) between the observed values and the values predicted

by the model. In the context of a distribution ID plot, this means that the model attempts to minimize the difference between positions predicted from the data according to a theoretical distribution such as Weibull, Log-Normal, etc. and the actual locations of the data. The result of the analysis provides a table containing, for each theoretical distribution considered, the value of the Anderson-Darling test (adj) and the value of the correlation coefficient. With the table comes also the graph of the data distribution. An example, for the station T10101 is show in figure 4.4 below. The Anderson-Darling test is a measure of how much observed data deviates from a specific theoretical distribution. A low value indicates that the observed data is very close to the theoretical distribution. This means that the selected theoretical distribution is a good model for the data. Instead, the correlation coefficient measures the strength and direction of the linear relationship between the ranks (cumulative percentages) of the observed data and those of the theoretical distribution, which means that a high value, close to 1, indicates that there is a strong linear relationship between the observed data and the theoretical distribution. When these two conditions are both satisfied, one can conclude with a high degree of confidence that the chosen theoretical distribution is very suitable for modeling the observed data. This is a strong indicator of a good fit, suggesting that the theoretical distribution is appropriate for describing the behavior of the data, both in terms of central location and variability. At this point it is possible to proceed to point two of the analysis.



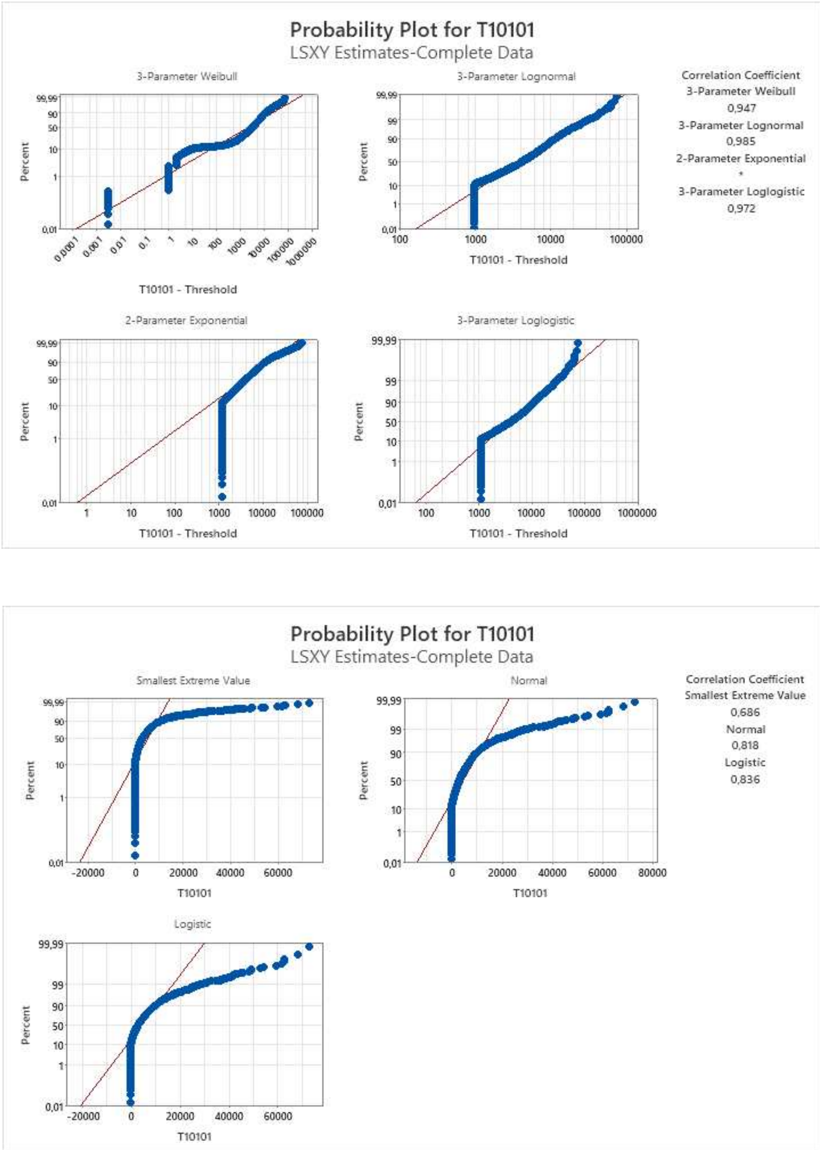


Figure 4.4: Graph, from Minitab, of the distribution ID plot for the station T10101

2. **Distribution Overview Plot**: In this case we know the most suitable theoretical distribution for modeling the data and we want to obtain the main information regarding this distribution. To do this in minitab we can launch a statistical analysis of the distribution analysis-right censoring type but this time with the Distribution Overview function. An example of the result of the analysis, for station T10101, is in figure 4.5 below.

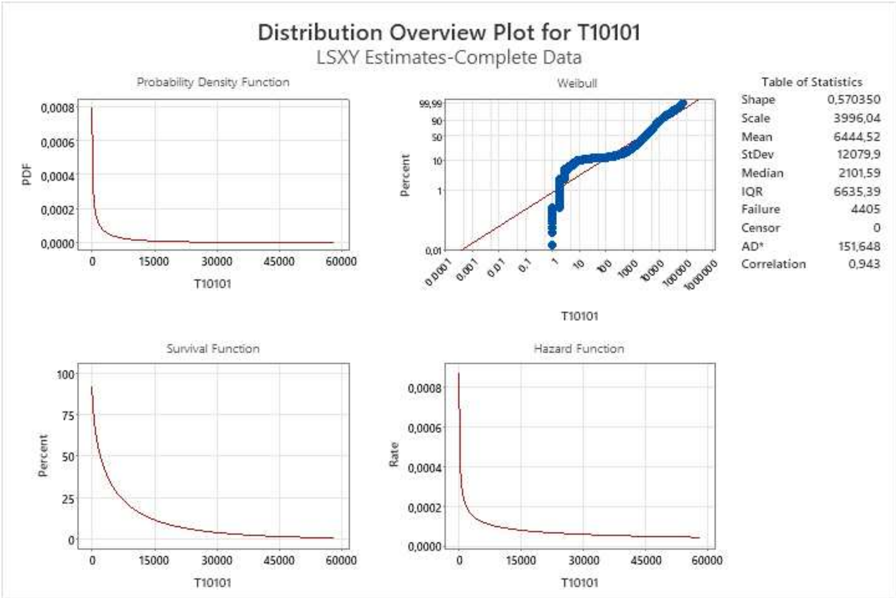


Figure 4.5: Distribution overview plot analysis for station T10101

Once the statistical analysis was performed in minitab, the results for each station were grouped in the table 4.9 below.

Processor	Statistical distribution	Scale	Shape	Processor	Statistical distribution	Mean	Std deviation	Processor	Statistical distribution	Scale	Location
Oljeboden	Weibul	20826	1,053	Miljöstation 3	Normal	24533	3048	T11101	Logistic	9491	20257
T10101	Weibul	39996	0,57	T11102	Normal	30035	20795	T27101	Logistic	8410	20870
T20101	Weibul	17643	1,07	T21101	Normal	20453	17795				
T20201	Weibul	12971	0,48	T22104	Normal	20065	16858				
T22103	Weibul	3078	0,36	T22105	Normal	23066	18510				
T23101	Weibul	11539	0,43	T23103	Normal	27861	22590				
T23102	Weibul	9837	0,42	T23104	Normal	19104	17951				
T30202	Weibul	11362	0,61	T30101	Normal	11078	11306				
T72301	Weibul	8463	0,43	T30201	Normal	19318	9494				
VF	Weibul	7024	0,39	T34101	Normal	15884	9603				
T20102	Weibul	8544	0,6	T35101	Normal	12696	13060				
Goods ut											
T90101											

Table 4.9: Results of the statistical analysis for each station

As can be deduced from the tables, the theoretical distributions that best approximate the data are Weibull and normal distributions.

The Weibull distribution is often considered an excellent distribution for approximating statistical data because it is very flexible due to the fact that it can adapt to different types of data depending on the values of its parameters. The main parameters are shape (k) and scale (λ). Depending on the value of k, it can take the form of an exponential distribution (k=1), be decreasing k<1 or increasing k>1. Since the analyzed data represents the duration times between the request for an order and the next for a station, the Weibull distribution allows the representation of both increasing and decreasing situations and therefore offers a good approximation of the data.

The normal distribution, on the other hand, is one of the most used in statistics. The reasons are different and ultimately it can be said that if the data derive from a large number of random factors or represent a symmetric distribution then it is likely that the normal distribution represents an excellent approximation of the data.

4.2 Scenario 1: Simulation with traditional transport vehicles

In this simulation scenario, call scenario 1, the forklift for material handling will be tested. The forklift is used to perform a delivery task between the production and the storage. Each task consist in delivery one unit load from the pick-up point to the drop-off point (see from to chart of transport order, table 4.2, for a detailed list of the transport order). The simulation scenario is show in figure 4.6 where the simulation model is represented. The objective is to measure the KPIs (that will be define later in this section) of the forklift and the machines to draw observations on the performance of the scenario.

Figure 4.6: Simulation scenario with forklift

Before starting the simulation, it is necessary to set the parameters of speed, acceleration, deceleration, loading time and unloading time of the forklift. The maximum speed value for the vehicle is 1.4 m/s. This speed is the maximum allowed by vehicles within the industrial environment of the company and is therefore equal to that of the AMR (next scenario, scenario 2). However, the acceleration and deceleration values of the forklift are different and are both equal to 1.3 m/s^2. To simulate the variability in the loading and unloading operations of the forklift, a normal distribution with a mean of 60 seconds was assumed. Therefore, the average time to load and unload the UDC is

60 s while to determine the standard deviation (σ), assuming that the data are represented on a normal distribution (it can be said that if the data derive from a large number of random factors or represent a symmetric distribution then it is likely that the normal distribution represents an excellent approximation of the data) an empirical rule was used. The rule of thumb is that about 68% of the data in a normal distribution will lie within 1σ of the mean, and about 95% of the data will lie within 2σ of the mean.

Furthermore, assuming that:

1) Under optimal conditions the operation can be completed in about 30s (minimum time)
2) In more complex conditions the time could take up to 90s (maximum time)

If we assume that most loading or unloading operations (e.g. 95%) are completed within 30 (e.g. when the operation is performed by an expert operator) and 90 seconds (e.g. when it is performed by a novice operator or in conditions that may make the operator uncomfortable) or within 2σ of the mean, we can calculate the standard deviation as:

2σ = 60s therefore $\boldsymbol{\sigma = \frac{60}{2} = 30s}$

Where:

Total range (95%) = 90s – 30s = 60s

So, in this hypothetical normal distribution, we have a mean of 60s and a standard deviation of 30s. At this point, the data was set in FlexSim to set the forklift load and unload parameters. In this way, we introduced the variability of the human operator by varying the loading and unloading times according to a normal distribution. Continuing to set the simulation parameters the simulation was set for a working day (2 shifts of 8 hours continuously starting at 6:00:00). Furthermore, the machines were set with the data provided by the company derived from the data analysis performed in the previous chapter. It is also notable that the machine are considered ideal so without setup up time and blocked. Subsequently, the KPIs for the machines were measured, namely waiting for transport and processing. The results of the machine KPIs are shown in the form of state bars in figure 4.7.

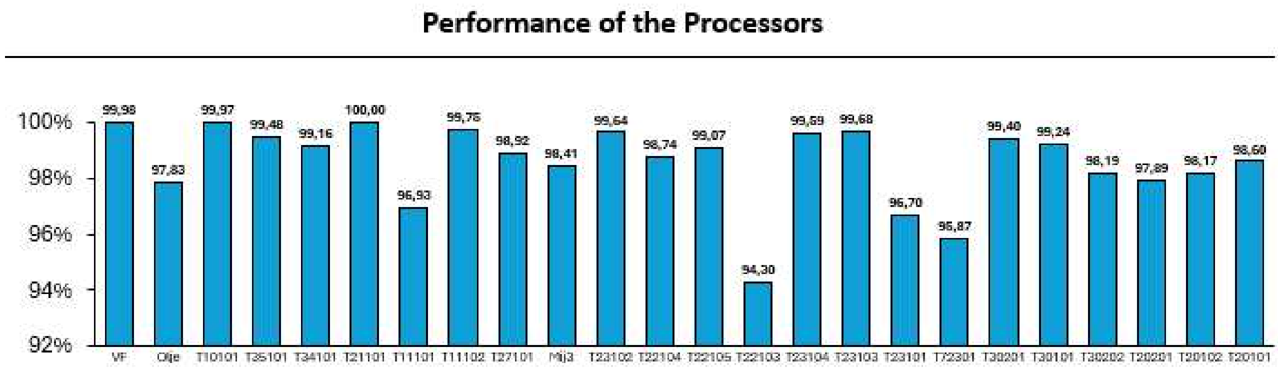


Figure 4.7: Performance of the processors for forklift scenario

The measurements show at most a decrease of about 6% in the processing status of the machines. This decrease occurs for the most critical station, T22103. The other stations that record a significant decrease in the processing status are: T11101 (3.07%), T23101 (3.3%) and T72301 (4.13%). On average for the rest of the machines the processing value is 99% and therefore with an average waiting time of less than 1% (less than 10 minutes of waiting). The most critical station is also the one with the highest total transport waiting time (6% of the simulation time). The highest waiting time for this station is mainly due to the distance from the warehouse and the higher demand, compared to the other stations, of transport requests (15 in a work shift), figure 4.8.

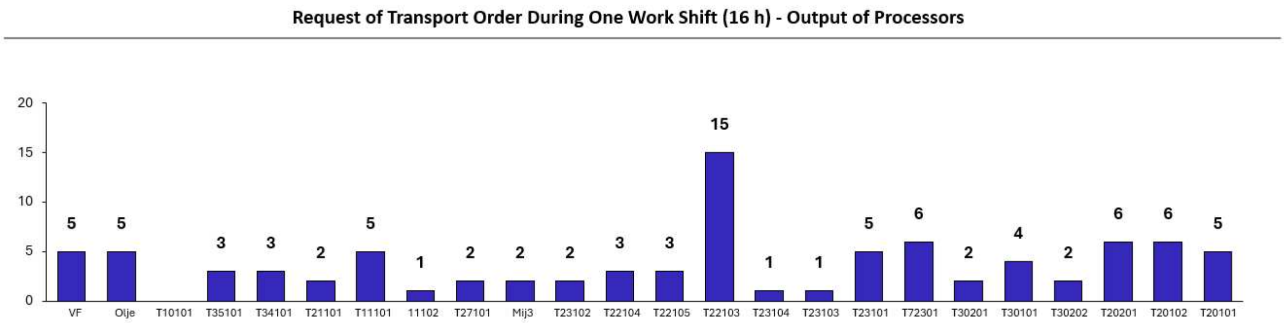


Figure 4.8: Output of the processor for forklift scenario

In general, the transport waiting time for stations is higher for longer vehicle loading and unloading times as evidenced by the forklift KPI measurements shown in figure 4.9.

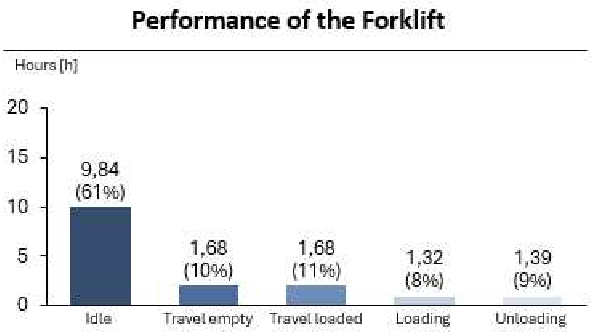


Figure 4.9: Performance of the forklift

The forklift KPIs measured values for the forklift, shown in figure X, are:

1) Idle time, equal to 61,48%
2) Blocked; 0%
3) Travel empty and travel loaded, respectively equal to 10% and 11%
4) Loading and unloading respectively equal to 8% and 9%

The forklift spends most of its time (61.48%) idle waiting for loading. There are no system blocks during operation and therefore it manages to complete all 89 simulated transport orders during the working day with loading and unloading times that occupy the vehicle for a total of 3 hours (about 1.30 h for loading and unloading).

4.3 Scenario 2: Simulation with AMR

In this section we will explain how the simulation analysis with AMR was conducted. In scenario 2 the AMR take the place of the forklift as task executer. Therefore, the AMR will do the same transport request as the forklift in the scenario 1 but this time the AMR parameter (acceleration, deceleration, loading and unloading time) are set in the simulation. In a first phase, the logic with which the simulation parameters were set is introduced. Subsequently, the outputs of the processors were analyzed to verify that the simulation was in line with the data provided by the company. Finally, the analysis of the simulation scenario, figure 4.10, and the results obtained are explained.

Figure 4.10: Simulation scenario with AMR

In this scenario, flexsim is used to simulate the internal material transport with AMRs. Once the processors and queues were connected to the AMR to simulate the real behavior of an AMR, the A* algorithm was added. A* is a navigation algorithm that allows the robot to make autonomous decisions, avoid obstacles and complete its tasks by choosing the fastest path.

At this point the AMR parameters have been set according to the data provided by the company, these are:

- Max velocity: 1,4 m/s

- Capacity: 1 load unit

- load time and unload time: 8 s

Once the AMR parameters were set, various simulations lasting a working day were then launched. The working day includes two work shifts, continuously, each lasting 8 hours and ranging from 6:00:00 to 22:00:00.

In the first analysis, the output of the processors and the contents of the queues were measured. This analysis confirmed that the simulation results are in line with the data provided by the company. In fact, during the simulation of the working day, 89 material movements were obtained compared to the maximum of 95 movements recorded by the company in 2022. The results of the capacity of each machine/processor are illustrated in the figure 4.11

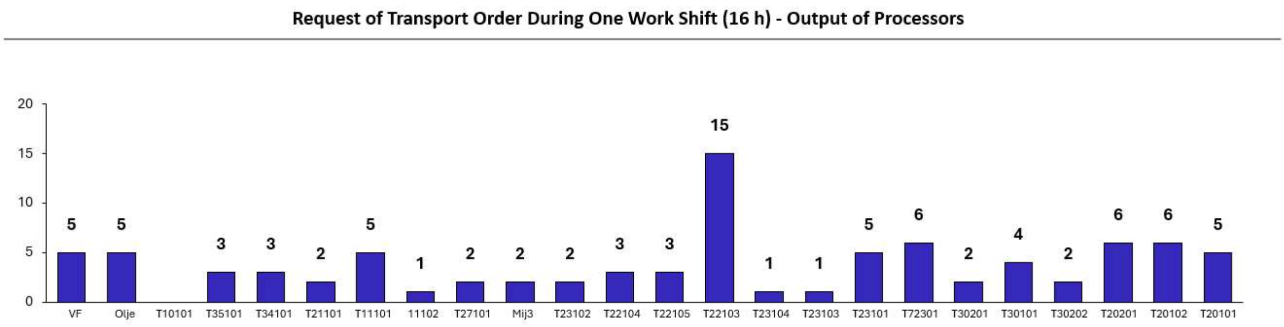


Figure 4.11: Output of the transport order during one work shift (16 hours)

To evaluate the performance of the scenario simulation, parameters were measured for AMR, expressed as percentages of the total duration of the simulation, these are:

- Idle: percentage in which the vehicle is not operational
- Blocked: percentage in which AMR is blocked
- Travel loaded: percentage of loaded trip
- Travel empty: percentage of empty trip
- Loading: percentage of time spent loading
- Unloading: percentage of time spent unloading

The results of measurements of these parameters are shown in figure 4.12

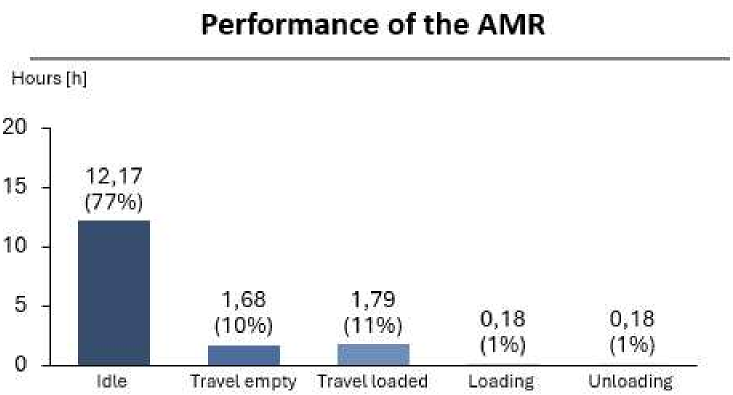


Figure 4.12: State Bar for AMR - performance in percentage and hours

From the measurement results it is possible to draw the following observations:

1) The blocked parameter is not displayed because no AMR blocking occurred during the simulation. This result is fundamental for testing the reliability of the AMR and confirmed that the AMR is capable of operating in complete autonomy and without interruptions.
2) The idle time of the vehicle corresponds to the majority of the operational time (77%). This result may be due to various factors including robot blocks (communication problems and malfunctions), system congestion or delays or waiting times due to a new assignment. To delve deeper into the value of this result, the blocked parameter is essential. Since this parameter does not record malfunctions or blocks of the robot, we can state that the result is in line with the data provided by the company because these are low-frequency transports and therefore the value of the idle time is high because the robot remains waiting for a new order (the charging time of the robot was not simulated and is therefore considered excluded from the factors determining the idle time). Furthermore, it is possible to confirm that the number of AMRs needed to satisfy transport requests is 1 in line with what was estimated with the theoretical calculation of the number of AMRs. For this reason, we did not continue with the simulation of a scenario with more than 1 AMR because it would not be convenient for the company and would also increase the idle time for both vehicles.
3) Travel empty provides the percentage of time spent by the AMR on unloaded trips. This parameter has the same value as the time spent on loaded trips, therefore each loaded trip corresponds to a similar unladen travel time in the simulation. We must try to reduce empty trips as much as possible because this is time spent inefficiently. Therefore, avoid empty trips so that every time the robot finishes a mission it returns to a strategic position or is immediately available for a new mission, avoiding unnecessary trips without a load.

Before drawing final considerations on the simulation results, it is necessary to evaluate the performance of the processors/machines, figure 4.13. To this end, the following parameters expressed as percentages of time on the total duration of the simulation were identified and measured, as in the case of AMR:

- Idle: measures the percentage of time the machine is idle.
- Processing: it measures the percentage of time in which the machine is working to produce the piece which will then have to be moved by the AMR
- Waiting for transporter: percentage of time in which the machine waits for the piece to be moved before moving on to the next phase.

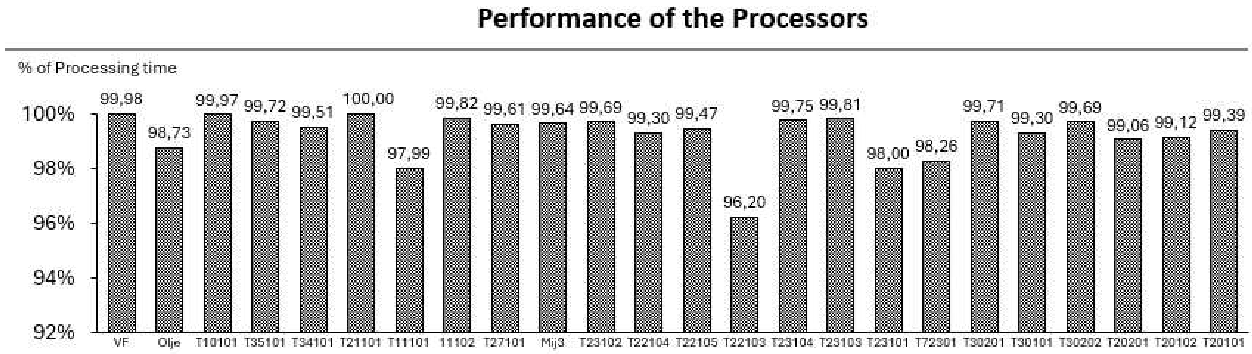


Figure 4.13: State Bar for Processors/machines

The results of the processing parameter, shown in figure As regards the waiting for transporter parameter, it is observed that only the T22103 processor records a significant value (3.8%) of time but nevertheless acceptable given the contained value. The results of this parameter make us understand that the machines are served well by the AMR and that there are no significant waiting times.

We can conclude by stating that in this scenario the AMR operates without blocks and interruptions while the machines are served optimally with waiting times on average under 1% of the total operating time. Furthermore, one AMR was found to be sufficient to meet transportation demands, in line with the theoretical calculation of the number of autonomous vehicles carried out in this chapter. The high idle time value for AMR, although due to the waits between one order request and another, some observations have been made to reduce this inefficient time. First of all, it is relevant in this case to increase the number of tasks for the AMR so that the robot is engaged and collaborates in more tasks and therefore reduces downtime. For example, involving him in other departments to transport material to multiple areas. Another solution could be to add shorter transports and therefore allow the robot to perform more movements with greater frequency. Another consideration concerns the optimization of mission planning using a management system that assigns tasks dynamically, for example by assigning minor tasks, preventing the robot from remaining idle for too long. These are just some observations that have been made for this case study but in other environments it may be necessary to make other observations that have not been considered here as they are not the purpose of this thesis, for example the optimization of maintenance through maintenance preventative or improve communication between man and machine.

4.4 Further Simulation

In this section, simulations of different scenarios with AMR are performed by increasing transport orders (i.e. decreasing the request deltas between one transport order and another) and simulating the interaction with operators. The aim is to verify to what extent an AMR is sufficient to guarantee acceptable performances for the machines in terms of waiting time of the station for the movement of the material. Furthermore, we want to verify the impact of a task performed by the operator on the performances of the AMR and the machines in the industrial environment object of the case study.

4.4.1 Increase of transport orders

In this section we want to simulate different production scenarios to find to what extent an AMR is sufficient to satisfy the transport requests. To do this, the transport request deltas between one order and the next were reduced for each station. The delta reduction was carried out by 10% for each simulation and up to 50%, then subsequently they were reduced by 70% and 90%. For each simulation, the performance parameters of the processors and the AMR were measured which, based on the results obtained, are used to identify the simulation scenario in which an AMR is no longer sufficient to satisfy the transport requests. It should also be noted that by decreasing the transport request deltas, the processor throughput increases. The results of the processor performance and the increase in throughput for each station for the seven simulations are shown in figure 4.14.

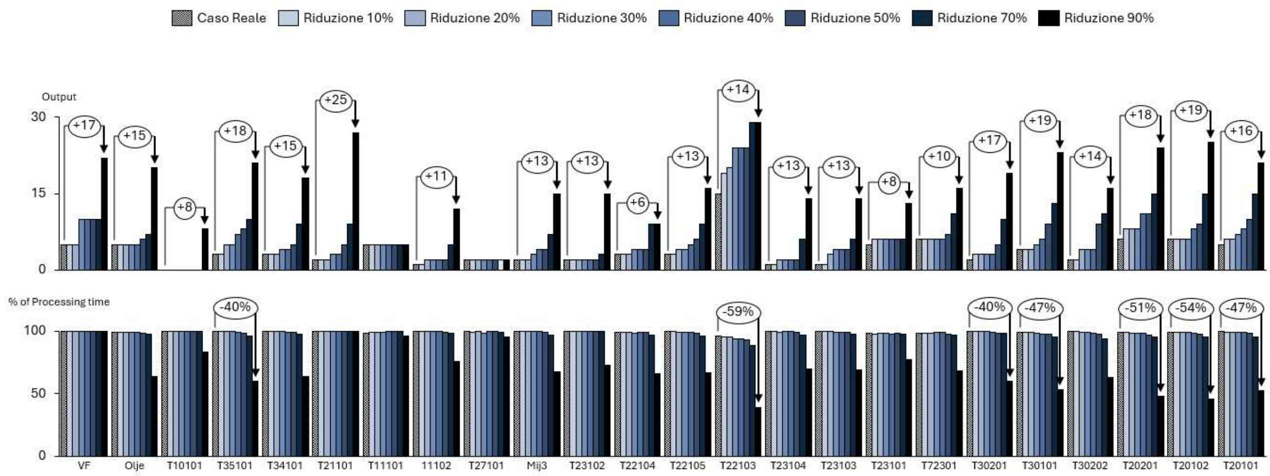


Figure 4.14: Performance of the processors and output for each station and for each simulation scenario

It is noted that in all seven scenarios the processor performances on average worsen as the transport orders increase. Only for the warehouse station (VF) and the T21101 station the performances do not worsen. In general, the performances worsen because by reducing the request deltas the transport waiting time increases because the AMR has more tasks to perform and therefore a single AMR is less and less advantageous. Up to a 50% reduction the processor performances are acceptable, however at a 70% reduction a significant decline begins. Despite this, the AMR manages to satisfy all the transport requests during a work shift up to 90% where instead this is not the case. With a 90% reduction in transport request deltas, orders increase dramatically and processor performance drops dramatically as shown in figure 4.8. The most critical station is T22103 which, in the case of a 90% reduction in transport orders, waits for the vehicle for up to 61% (approximately 10 hours) of the work shift time (16 hours), figure 4.15. The waiting time is so high also because the station is distant (160 m) from the unloading and loading point, i.e. from the warehouse.

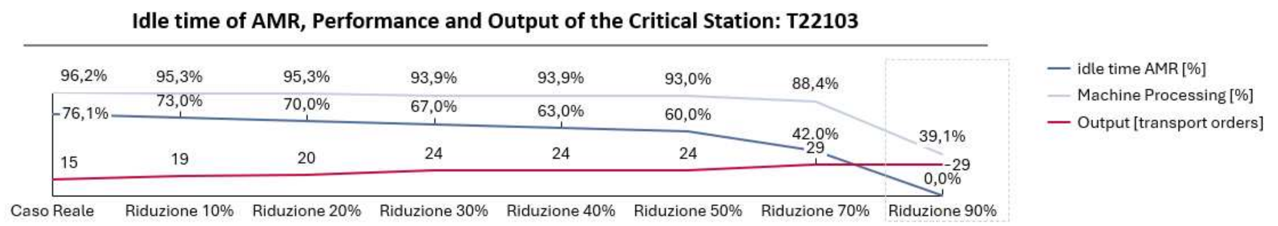


Figure 4.15: Idle time, performance and output of the critical station: T22103

With a 90% reduction, a single AMR is not sufficient to satisfy all the transport requests of the work shift (361 out of 404 transport requests completed by the AMR). This is also evident from the AMR performance measurements. The idle time is zeroed (100% decrease), the empty and loaded travel time increases, occupying the AMR for 90% of its operating time, figure 4.16. The remaining available time is occupied by the AMR for the unloading and loading of the unit loads (10% of the total time). The decrease in idle time is due to an increase in the use of the AMR which is completely occupied by transport tasks. It is therefore necessary in this case to increase the number of AMRs to two to satisfy all the transport requests of the stations.

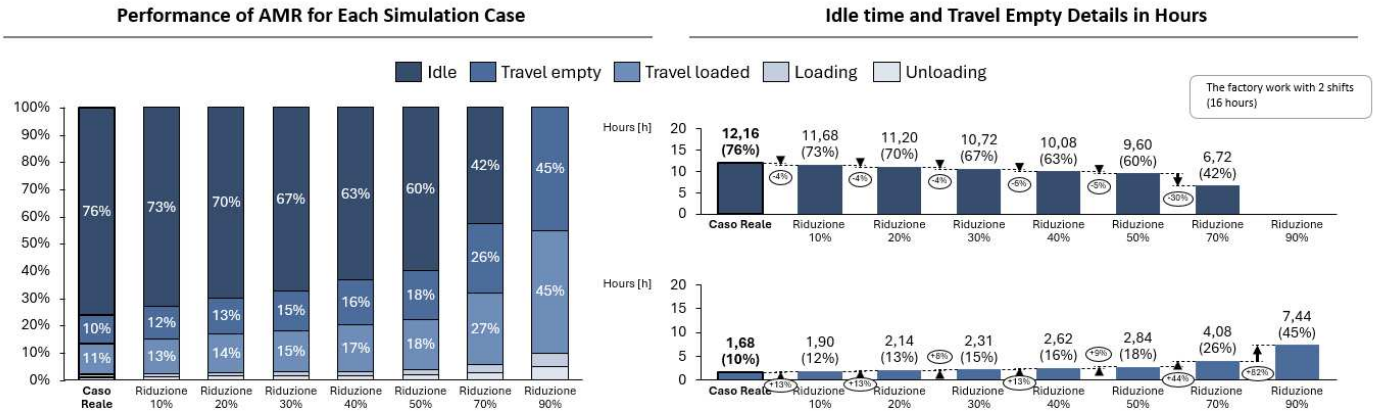


Figure 4.16: Performance of the AMR and idle time and travel empty detailed in hours

4.4.2 Interaction with the operator

In order to complete its tasks, the AMR must travel along the corridors within the production system where the operators also work and therefore share the space with the robot. Therefore, in this case study the AMR could come into contact with the operator. In this section the objective is to understand if in the real operating conditions of the transport system the AMR comes into contact with the operator and if this interaction affects the performance of the transport system. A task assigned to the operator requires that he crosses the corridors and therefore interacts with the AMR, as in figure 4.17. The AMR has the ability to stop in front of an obstacle such as an operator and then resume its path once the road is clear. We therefore want to test whether the blocking of the AMR due to the interaction with the operator alters the performance of the transport system of the case study for the task assigned to the operator.

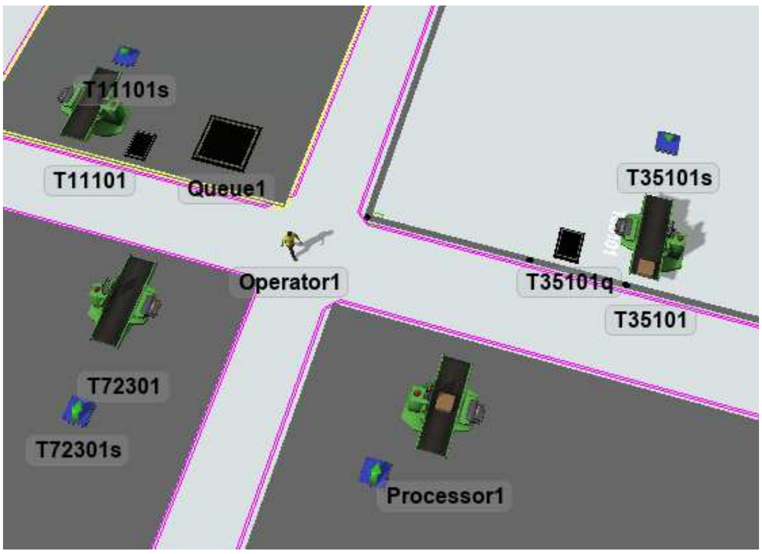


Figure 4.17: Scenario with operator: Operator crossing the corridor to complete his task

To simulate the interaction, an operator assigned a transport task was introduced into the simulation scenario. To complete the task, the operator (operator 1) must collect the material exiting the machine (processor 1) and transport it to a storage point (queue 1), figure X. Within the company's industrial environment, the task assigned to the operator is to transport materials from the production area to the assembly area. The material exiting the machine is expected every 30 minutes, i.e. a unit load must be transported by the operator every 30 minutes. The task requires the operator to cross the corridor and therefore the possible interaction with the AMR. In Flexsim, to simulate the interaction, a proximity system was introduced. The proximity system allows you to set functions to stop the task excuter, i.e. the AMR. To set these functions, two simple codes were written to simulate two main events of the interaction between the operator and the AMR.

The first event is the AMR meeting with the operator and the second event is to make the AMR resume its path. For this purpose, to stop the robot, the first code was written to stop the robot two meters before the meeting with the operator. The code is:

```
/**Custom Code*/

Agent agent = param(1);

Agent neighbor = param(2);

int numInProximity = param(3);

stopobject(model.find ("amr"),1);
```

At this point, the robot stops to let the operator who crosses the road pass, but then the robot must resume its path to complete its task. To do this, the following custom code was written:

```
/**Custom Code*/

Agent agent = param(1);

Agent neighbor = param(2);

int numInProximity = param(3);

resumeobject(model.find ("amr"),1);
```

Once these codes have been entered and the connections between the two "task executers" (AMR and operator) have been set up, it is possible to start the simulation of the work scenario, as in the previous scenarios, except that the AMR now recognizes the operator and stops when he is within a radius of 2 meters. The simulation results are shown in figure 4.18.

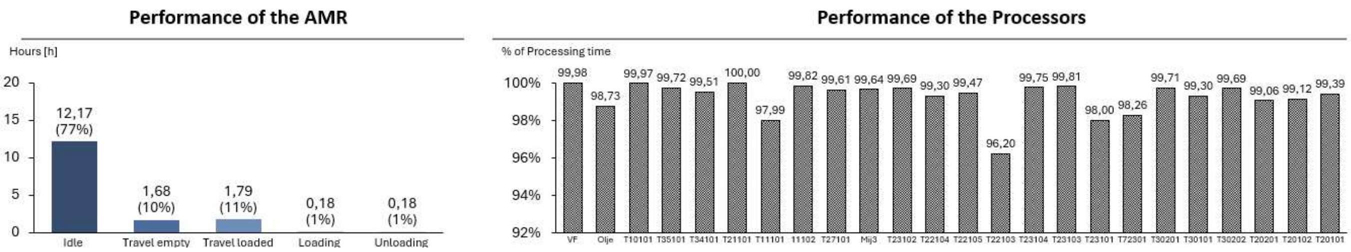


Figure 4.18: Scenario with operator: performance of the AMR and performance of the processors

From the results of the KPIs of the machines and the AMR, it is noted that, for the task assigned to the operator and introduced in the simulation model, the influence of the interaction with the vehicle does not impact the transport system. The KPIs measured for the AMR show the same values as those shown with the simulation without an operator. Therefore, the machines also record the same values of processing and waiting for transport as in the case without an operator. The request for low-frequency transport means that the operator and the robot never meet and therefore the transport system works without interactions. It should also be noted that the operators are trained to interrupt the AMR as little as possible during its operation so as not to hinder it in completing its task.

5. CONCLUSION

In this chapter the conclusions of the thesis will be discussed. The chapter is organized in three main parts: first the results of the qualitative analysis will be discussed to answer the first research question, secondly the results of the quantitative analysis carried out with the simulation software will be discussed and finally possible future research on AMR in the intralogistics environment will be presented.

The use of AMRs in the intralogistics environment and the impact of the characteristics of this environment on the robot components have been investigated qualitatively in a non-exhaustive way. The comparison between AMRs and traditional vehicles has not been qualitatively investigated but only quantitatively. However, the analysis carried out has allowed us to answer the research questions and therefore to achieve the objective of the thesis.

5.1 Qualitative Discussion

In conclusion, this thesis has qualitatively discussed an analysis of the use of autonomous vehicles and in particular AMRs in the intralogistics environment and the impact of this environment on the robot components.

The characteristics of the AMR, namely: the decentralized control system, the support platform, the possibilities of performing tasks in collaboration with the operator, the scalability of the system, the ability to avoid obstacles and to reach the goal by optimizing the path make it an attractive system for companies in the use of intralogistics operations. However, it is necessary to pay attention to the environment in which these vehicles are introduced because otherwise they can lead to inefficiencies of the system and constitute an additional problem for the company to solve. For this reason, the qualitative analysis focused on the impact of the characteristics of the intralogistics environment on the components of the visual-based technology that make up the AMRs. Hardware components such as sensors, the locomotion mechanism and other components such as batteries and processors can be put to the test by the industrial environment if special attention is not given. The same also applies to the software components of the robot that constitute the heart and the thinking mind of the AMR. The interaction of the robot with the industrial environment, divided into five areas (layout complexity, human interaction and vehicle interaction, floor condition and atmosphere condition, network connection and finally unit load), has allowed us to identify the impact on the AMR components for each area. When introducing an AMR, it is important to first study the layout of the operating environment. This must have corridors that allow the vehicle to pass safely and to carry out maneuvers safely. Furthermore, objects along the path (shelves, pallets) that can slow down the AMR, hindering it or even block it must be taken into account. It is therefore necessary to keep an orderly environment, leaving space in the corridors for the AMR to pass through and positioning the loading and unloading points strategically so that the AMR can operate in the best conditions. When the AMR shares an environment in which different transport systems and operators interact, such as in intralogistics, it is necessary to take this aspect into account. A fundamental problem of the interaction with other vehicles concerns the congestion of the system. Obstacle avoidance sensors and motion and path planning software are put to the test in heavy traffic situations. In addition, interaction with system operators is challenging for AMR sensors to maintain an adequate level of safety. It is therefore necessary to educate operators to collaborate with robots and share spaces. Furthermore, it is necessary to try to limit as much as possible the interaction during vehicle movement with the operator through the use of dedicated corridors and rest and transit areas. In the industrial environment when operating with AMR it is necessary to take into account the floor conditions and the atmosphere in which the vehicle operates. The floor conditions can impact both the software and hardware features. Dirt on the floor such as oil stains or floors with deformations such as holes make it difficult for the robot to move and its movements impact the locomotion system as it was possible to observe during the visit to the company. Atmospheric features such as temperature changes or excessive humidity must be kept under control because they can impact the robot's localization system by creating noise sensors. Another aspect of the industrial environment to take into consideration is the network connection. The AMR fleet can communicate in real time with each other or with other systems in the production environment (automated workstations, elevators, doors, etc.) via wireless protocol systems. This type of communication is often used via a Wi-Fi connection for small fleets. The challenges related to wifi communication include limited/spotty coverage, undependable handoffs between access points, declining bandwidth, unpredictable latency. It is therefore necessary to maintain a stable connection in all areas of operation of the AMR, even the most remote ones, to avoid system blocks. Finally, in an intralogistics system the AMR used for material handling, in addition to interacting with operators and other vehicles, must interact with the load unit (UdC). The UdC can vary in shape and weight and the AMRs must be equipped with adequate tools to handle it. In the case observed in the company, the introduction of the AMR forklift used for handling pallets (1200 x 800 mm) is challenging for the AMR sensors. When this is used to handle different shapes of UdC loaded on the pallet, the sensors can be covered, causing the system to block. It is therefore essential to design the UdCs to be handled with the AMR so that they do not hinder the robot in completing the task.

The discussion of the qualitative analysis just described is summarized in the table below where the impact on the AMR components at both hardware and software level is identified for each characteristic of the industrial environment.

Industrial Environnement	**Impact on AMR components** **Hardware**	 **Software**
• Layout Complexity	*Sensor*: Exteroceptive sensor (distance and Lidar)	*Navigation*: Path Planning, Motion Planning e Simultaneus localization and Mapping
• Human Interaction and Vehicle Interaction	*Sensor*: Exteroceptive sensor (distance and Lidar)	*Navigation*: Local Path Planning, Motion Planning, Mapping
• Floor Condition and Atmosphere Condition	*Sensor*: Exteroceptive sensor (distance and Lidar) *Wheel locomotion*	*Navigation*: Localization
• Network Connection		*Navigation*: Localization
• Unit Load	*Sensor:* Exteroceptive sensor	*Navigation*: Localization and Mapping

Finally, to answer the first research question:

RQ1: *What are the characteristics of the production environment that impact the operation of AMRs? Are these characteristics a prerequisite for the operation of AMRs?*

The characteristics of the intralogistics industrial environment that impact the operating of AMRs concern layout complexity, interactions with vehicles and operators, floor condition and atmosphere condition, network connection and finally unit load. These characteristics impact the hardware and software systems of the robot and must be a prerequisite to effectively introduce AMRs into the intralogistics system and for efficient material handling.

5.2 Quantitative Discussion

In this section of the chapter, the results of the quantitative analysis performed with the simulation software will be discussed in order to answer the second research question.

First of all, this quantitative analysis focused on the case study, therefore the results and observations made are valid only with the hypotheses and for the data of the case. After an analysis of the data provided by the company, the comparison between the two simulation scenarios was carried out first by testing the performance of the scenarios, that is, by measuring key performance indicators (KPIs). These KPIs are measured both for the means of transport (AMR or Forklift) and for the processors, that is, the machines. It should be remembered that for the AMR, the selected KPIs are: idle time, load and unload time, travel load and travel empty, blocked. For the processors, on the other hand, they are: processing (measures the percentage of the machine working and therefore not waiting for a transport request) and waiting for transport.

First, the scenario was simulated with AMR and the KPIs for the case study were measured. The machines, considered ideal, are well served by the AMR (processing on average around 99%) with acceptable waiting times (on average less than 1% or 16 minutes). However, it is worth noting a more critical station (T22103) where we have: processing 96.2% waiting for transport 3.8%. These results are due to the higher transport requests generated by a higher flow rate and the high distance (160 meters) from the warehouse. Instead, the analysis of the AMR KPIs shows that it is idle most of the time (76%). This result is in line with the analysis of the processor data as it further demonstrates the low frequency of transport requests (maximum 95 transport requests recorded in a working day in the year 2022 by the company). To reduce the AMR idle time and therefore optimize its operating time, it is best to reallocate it to other transport tasks. Therefore, to simulate this case, the deltas of requests between one transport order and the next for each station were reduced while maintaining the statistical distribution of the data unchanged. The capacity of the machines or simulation processors was therefore increased by reducing the deltas by 10%, 20%, 30%, 40%, 50%, 70% and 90%. The processor output, i.e. the capacity of the machines, goes from 89 (real case) to 404 (90% reduction). In this way, as expected, the idle time of the AMR is reduced from 77% to 73% (10% reduction), then to 70% (20% reduction), to 60% (50% reduction) and finally to zero for the 90% case. The performance measures of the machines, i.e. the processing state and the transport waiting percentage, worsen. The processing state in general decreases for almost all stations and the transport waiting time increases up to 61% (about 10 h) for the most critical station (T22103) in the case of a 90% reduction. It is therefore concluded that an AMR is able to satisfy the transport requests up to a 90%

reduction of the request deltas between one transport and the next and therefore from 90% onwards at least 2 AMRs are necessary. The second AMR would not only lead to the completion of all simulated transport tasks in a shift but would also improve the performance of the processors. As for the simulation with operator interaction, the AMR does not come into contact with the operator when the transport request occurs every 30 minutes as in the case in question. This could come into contact with the robot if the transport request time decreases or increases but this is not the case in question. Therefore, the KPI results for the machines and processors remain unchanged and therefore equal to the simulation with AMR. Once the simulation results with AMR were obtained and commented, we moved on to the simulation of the second scenario with forklift. The aim is to simulate the same transports that were previously carried out with the AMR but replace it with a traditional vehicle, namely the forklift, which the company used for the transports analysed. To this end, to make the comparison, the technical characteristics of the forklift were set, namely the acceleration and deceleration times (the speed of the two vehicles remained the same, 1.4 m/s, for safety reasons). Furthermore, to model the variability of the human operator, different loading and unloading times of the vehicle were set according to a normal distribution in order to simulate the variability in the loading and unloading times of the forklift driven by the operator. It should be noted that this is not the only way to make the comparison but it was decided to set up the comparison based on the data available and the objective of the second research question. The results obtained from the KPIs for the traditional vehicle show a reduction (19%) in idle time and an increase in loading and unloading times (624% and 660% respectively), figure 5.1.

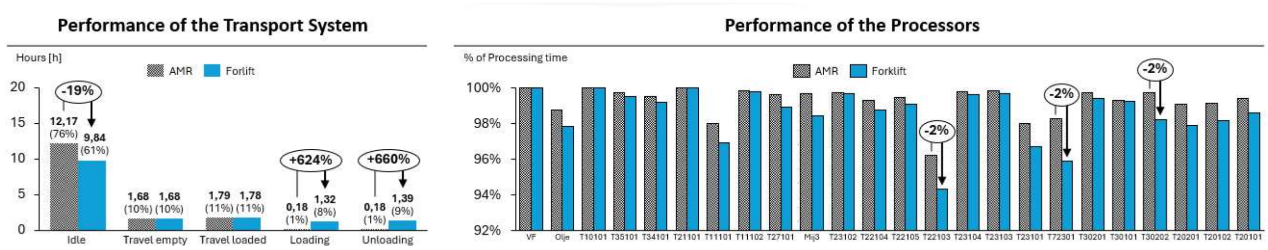


Figure 5.1: Comparison between AMR scenario and Forklift scenario

This result is due to the increase in time for the operator to load and unload the load units. The most critical station remains the T22103, in this case however the total waiting time of the station for the transport is about 57 minutes (about 18 minutes more than the AMR). Furthermore, the processing times of the stations Oljeboden (0.9%), T35101 (0.24%), T34101 (0.35%), T11101 (1.06%), T27101 (0.69%), Mijolstation3 (1.23%), T22104 (0.56%), T22105 (0.4%), T23101 (1.3%), T72301 (2.39%), T30202 (1.5%), T20201 (1.17%), T20102 (0.95%) and T20101 (0.79%) are particularly worse than in scenario 1. In general, we can say that the processors record a higher waiting time and therefore worse performance (waiting for transport increases by 1-2%) compared to the simulation with AMR: the percentage of processing state is lower (1-2%).

In conclusion, to answer the second research question, namely:

RQ2: What are the advantages, in terms of performance of the transport system, of using AMRs for material transport compared to traditional transport systems?

The advantages in terms of performance of the transport system in using AMR concern the reduction of the waiting time of the stations, the reduction of the times to complete the task by the AMR and therefore the possibility of using the vehicle in other activities (given the higher idle time of the AMR). Reducing the waiting time of the machines increases the processing state and therefore the possibility of producing more. Furthermore, with the introducing of the AMR in the transport system it is possible to reallocate the operator from a non-value added activity (transport of material with the forklift) in a different task with value added. It is important to note that these results were obtained for the case study in question with the hypotheses of an ideal machine, i.e. without set-up times and failures, therefore they cannot be applied to other industrial contexts unless the hypotheses of the case are made.

5.3 Further Research

In this section, possible future research related to the topic covered by the thesis is explored. As regards the characteristics of the industrial environment on the influence of AMR performance, the analysis to answer the first research question was carried out only at a qualitative level without going into greater detail at a quantitative level. In particular, it would be interesting to delve deeper into the influence of the load unit on the choice of means of transport and see how this affects the functioning of the AMR. The customization of the load unit (udc) can facilitate transport with AMR and this aspect could be investigated at a quantitative level by testing the performance of the AMR by varying the udc. Another aspect of the characteristics of the industrial environment that could be further explored concerns the interaction with the operator. In this area in particular, we refer to the human-machine interface with which the operator can interact with the robot. The interface between man and machine can signal the status of the robot and intervene preventively before failures or stops occur. I believe this aspect is important to improve the performance of the robot and increase productivity.

As regards the comparison between traditional vehicles and AMR, this thesis has been carried out by applying it to a specific business case. Future research could focus on extending the comparison at a quantitative level by including different categories of means of transport (such as tugger trains) with different load capacities and testing the system performance in the same way. Furthermore, in future research, the ability of the AMR to optimize the route could be tested and compared with traditional vehicles that are instead guided based on the operator's experience. As regards the interaction of the robot with the operator, it would be interesting to understand how much the performance decreases based on how many stops of the vehicle occur during its operation due to the interaction with the operator.

In the simulation with Forklift it was not possible to test the variability of the human factor. In this case, the variability of the human factor refers to the operator's ability to complete the transport of the load. In particular, regarding the variability of transport times with forklift, it refers to the choices made by the operator that can depend on the one hand on the experience of the forklift driver and on the other on the health and concentration of the operator. However, it was possible to vary the loading and unloading times by assuming a normal distribution and therefore vary the time of these operations. It should be noted that compared to the forklift, the AMR does not encounter performance problems of this type because it is able, unless there are system malfunctions, to maintain the same performance. System malfunctions can be traced back to the factors and characteristics of the industrial environment mentioned in the previous chapter.

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