TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

OPTIMIZATION OF PRODUCTION INTRALOGISTICS FOR EFFECTIVE USE OF AUTONOMOUS MOBILE ROBOTS

TOOTMISE SISELOGISTIKA OPTIMEERIMINE AUTONOOMSETE MOBIILSETE ROBOTITE EFEKTIIVSEKS KASUTAMISEKS

MASTER THESIS

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Tallinn 2023

(*On the reverse side of title page*)

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Department of Mechanical and Industrial Engineering

THESIS TASK

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Thesis topic:

(in English) Optimization of Production Intralogistics for Effective use of Autonomous Mobile Robots

(in Estonian) Tootmise Siselogistika Optimeerimine Autonoomsete Mobiilsete Robotite Efektiivseks Kasutamiseks

Thesis main objectives:

1. Analyse the current AMR material handling flow in production.
2. Identify the bottlenecks and efficiency problems.
3. Propose improvement ideas and solutions.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Creating the thesis structure	March 5
2.	Systematic Theoretical Analysis	March 25
3.	Process Analysis and Simulations	April 15
4.	Process Improvement Detailing	April 30

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PREFACE

Thesis has been conducted by Turan Azizov, who is a graduate student in the Department of Mechanical and Industrial Engineering at Tallinn University of Technology. Author would like to express deep gratitude to all parties who supported and contributed in the process.

Establishing and maintaining efficient production intralogistics is highly complex and requires complete understanding of entire supply chain process. This thesis helps to analyse and identify problems with the Autonomous Mobile Robot involvement in the company intralogistics. Thesis aims to create a framework and provide solutions and improvement ideas to better utilize Autonomous Mobile Robot fleet in the given company. Thesis work can later be expanded and used for implementation processes in the practical settings.

Keywords: AMR, intralogistics, optimization, simulation, master's thesis

List of abbreviations and symbols

AMR – Autonomous Mobile Robot

KPI – Key Performance Indicator

AGV – Automated Guided Vehicles

ERP – Enterprise Resource Planning

SAP - Systemanalyse Programmentwicklung

MIR – Mobile Industrial Robots

LoPS – Local Planning System

GloPS – Global Planning System

WMS – Warehouse Management System

SLR – Systematic Literature Review

NPI – New Product Introduction

PLC – Programmable Logic Controller

TMS - Transport Management System

UA – Unified Architecture

RFID - Radio-frequency identification

ROI – Return on Investment

AI – Artificial Intelligence

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INTRODUCTION

This thesis discusses production intralogistics and material handling processes in a manufacturing company in Estonia with the focus on optimization of production intralogistics. There are different types of material handling equipment operational on the layout. However, considering the allocated time period for this research, only Autonomous Mobile Robot (AMR) process will be analysed. The addressed problem in the light of selecting such topic is the low-level utilization rates of the mobile robots in the production layout. Lower utilization rates in material handling can be viewed as the signs of low-level productivity, decreased efficiency, and increased product unit cost.

The research will focus on improving the utilization of AMR considering current setting. Characteristics, requirements, and challenges of existing material handling process will be analyzed. Considering current state of the company and the research studies and alongside with numarical analysis, the research study aims to address the following general research questions and provide answers to them:

1) What are the requirements and challenges of material transportation in production intralogistics?
2) How to organize, plan and control AMRs for material transportation in intralogistics for better utilization?
3) How to organize robust AMR setting against seasonal demand changes?

Insight, on which decision support methodology can be built, will be provided. Additionally, thesis will offer guidance for planning and managing AMRs in intralogistics to enhance the flexibility, productivity, service, quality, and cost performance of material transportation. Finally, it will encourage the transition from semi-automated to fully autonomous material transportation and maintain optimal intralogistics. The scientific analysis will be conducted with help of Scenario Simulations in Visual Components software. Moreover, mathematical modeling approach will be utilized to establish a connection between demand rates and number of robots.

Overall, first part of the report will be related to research scope and its importance for the particular case. This part will be followed by Systematic Literature Review (SLR), in which selected topics and methodology from major and significant existing papers in the fields of material handling, mobile robots, intralogistics in the past 20 years will be discussed and analyzed. In Methodology part, the systematic approach will be proposed by the author and its relevance and possible value will be discussed. After that improvement ideas will be provided and discussed. Finally, cost assessment will be made based on the implementation plan and feasibility and profitability will be investigated.

1. IMPORTANCE OF THE TOPIC AND MOTIVATION

In today's world, many major companies face difficult financial challenges in the light of current economic conditions. These difficulties mainly result from shifts in consumer behavior, market disruptions, heightened competition, changes in the law, and world economic events. Because of this, businesses must adopt a strategic and proactive approach to address these issues and guarantee their long-term financial stability. This could entail mainly putting cost-cutting measures into place [1].

Material handling is an important element in a supply chain and plays a critical role in enabling efficiency and contributing to customer satisfaction [2]. In general, material handling does not add value to the final product, rather it is part of the product cost. Reducing costs and sale prices, therefore, ultimately increasing profitability is one of the major concerns of a manufacturing company in order to survive in a competitive market [3].

Warehousing and material handling enable matching vendor supply with customer demand, adjusting product or package specifications, and planning distribution activities [4]. In other words, by lowering inventory levels, requiring less time and effort to transport items, and streamlining storage and handling procedures, effective material handling lowers costs and boosts productivity. However, non-productive and faulty material handling may result in disruption in the material flow, therefore, downtimes in the production [5]. So, it is very essential for the production management to have optimized manufacturing intralogistics.

One of the main objectives of manufacturing businesses is to choose the best material handling equipment that, when properly used by the workforce, may lower fuel costs, production times, and prices while also boosting the plant's overall productivity and profitability. Up to 55% of the total plant space, 25% of the labor force, 87% of the total production time, and 15% to 70% of the total manufacturing costs can be devoted to material handling activities and equipment [6]. There are several equipment used for material handling in the context of production intralogistics. These include forklifts, conveyor belts, pallet jacks and so on. The main disadvantages of these options are related to limited flexibility and existence of manual steps in the processes that necessitates human factors in the process. This paper will discuss the Autonomous Mobile Robots (AMRs) as the main material handling equipment type. According to past research and practices, introduction of AMRs into the flow allows better transformation to the Industry 4.0 environment and better encourages the idea of a flexible and cost efficient manufacturing system [7].

Many big companies include AMRs for more efficient and faster material handling. However, there are some issues that hinders AMR to reach their maximum level of productivity. Problems are mainly unique to the production facilities and sites, especially when layouts are dynamically changing in certain frequency. In this paper, we will focus on providing a certain method for dynamic layouts for better AMR integration. Moreover, equipment standardization will also be considered. As a use case, one of the company’s current intralogistics will be simulated and analyzed. Improvement ideas will be proposed and different scenarios will be simulated and KPIs will be measured.

It is important to seize the inefficiencies in the current system. However, it is not an easy task when the operating area of the robots is quite vast. There are several ways to monitor and make conclusions regarding the current environment with the help of visual management methodology. This includes dynamic dashboards, Value Stream Mapping, Simulations and so on. In the use case, analysis will be mainly concluded based on 3D Simulations as they will be more beneficial especially when we analyze different scenarios. The research approach of simulation modeling was chosen to examine the difficulties of a material handling system in intralogistics because it enables quantifying and watching the system's behavior under various conditions [8]. Simulation method also allows users to analyze the current situation and different scenarios without taking any risks in real layout. When inputting the data correctly, it can provide the output that is close to the possible real values. Most of the simulation softwares includes the real time statistics integration. This will allow for better visualization and analysis.

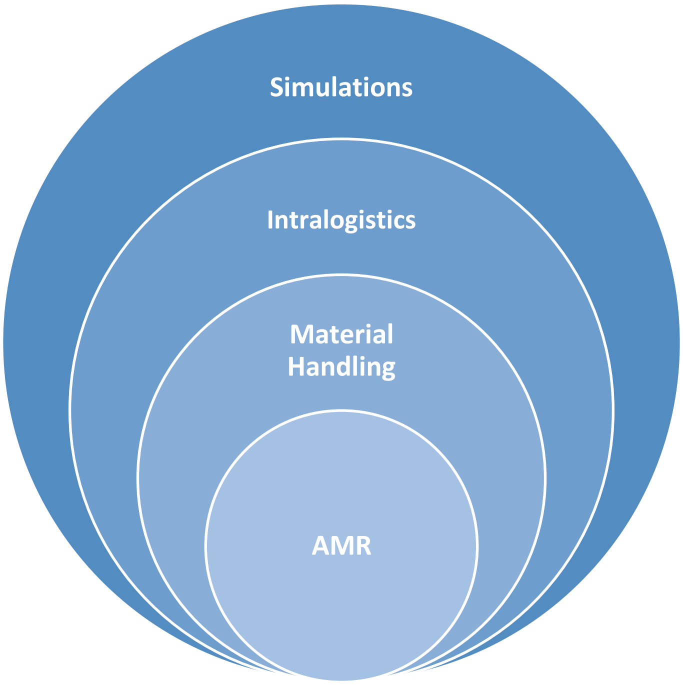

Figure 1. Research Scope

Thus, manufacturing companies must optimize material handling in semi-automated production intralogistics in order to lower costs, increase productivity, and boost profitability in a super competitive market. The use of autonomous mobile robots (AMRs) in manufacturing systems holds promise for increasing flexibility and lowering costs. The standardization of equipment and dynamic layouts are two issues that must be resolved if they are to maximize their productivity. A useful tool to recognize, evaluate, and suggest solutions to these problems without putting actual construction at risk is simulation modeling. Thus, in the current economic climate, manufacturing companies can achieve long-term financial stability and success by utilizing simulation modeling and investing in material handling optimization.

2. SYSTEMATIC LITERATURE REVIEW

A research technique used to gather, assess, and examine pertinent literature on a particular subject or research issue is called a Systematic Literature Review (SLR). It entails a thorough and in-depth search for existing literature, including scholarly publications, papers, and other pertinent sources, as well as a critical evaluation of the quality and applicability of the studies.

The search strategy, inclusion and exclusion standards, data extraction procedures, and analysis techniques are all outlined in a pre-established protocol for systematic literature reviews. A systematic literature review's objective is to present a thorough and objective overview of the available data on a given subject. This information is frequently used to direct future research, uncover knowledge gaps, and assist decision-making.

2.1 Production intralogistics

Production intralogistics is defined as the a complex interplay of multiple logistics functions that covers the organization and control, execute, optimize the internal material and information flows [9]. To ensure maximum effectiveness and productivity, this includes structuring and managing the production process, carrying out required tasks, and optimizing internal flows. Therefore, production intralogistics is a crucial component of any contemporary manufacturing operation and determines the effectiveness of the production process.

The need to control the flow of information and materials throughout the production plant lies at the core of production intralogistics. Suppliers, production managers, and logistics staff are just a few of the numerous stakeholders that are involved in this complicated web of interactions. For the manufacturing process to run efficiently and for products to be delivered to customers on time and in good condition, these interactions must be managed effectively.

Establishing productive and cost-efficient logistics is difficult due to highly complex behavior of the supply chain. In the manufacturing industry, the operations are highly complex starting from raw components all the way to the final product that the customer receives. Focusing on the manufacturing processes, it is necessary for the production to maintain the flow between different departments. In other words, inbound and warehouse should supply the production line with flow of needed materials and kitted batches.

Uninterrupted flow of materials allows the production line to work without downtimes (except for technical stops) and keep up with the takt time. Takt time, which is the available production time divided by customer demand [10], is the metric used to identify the needed cycle time to be achieved in order to meet the customer demand in time. In other words, delivery delays occurs when actual product cycle time is less than takt time. However, the delivery without delays transforms to better customer satisfaction and better competitive position. It can be mentioned that the production cycle time is dependent on many factors and can be highly affected by unplanned activities, such as machine breakdowns or software downtimes. Another factor is related to material handling. Especially when the production lines work continuously, it is very critical to supply the line with needed components and workforce. Otherwise, production stops and causes delays. Such downtimes are extremely costly in many ways especially in peak demand times, when any delays with customer delivery might damage the reputation, reduce trust, and adversely affect the market share.

Companies need a thorough grasp of production intralogistics and how it can affect their operations if they want to succeed in the fiercely competitive manufacturing sector. This calls for a willingness to engage in the required technology and infrastructure, as well as a dedication to ongoing optimization and improvement. Companies can put themselves in a successful situation in the rapidly changing manufacturing industry by concentrating on the needs of their clients and by streamlining their internal information and material flows.

2.2 Material handling

Material handling involves the flow, safety, storage, and control of components and products throughout manufacturing, warehousing, distribution, consumption and disposal processes. The aim of material handling is to perform given activities at low cost, in time, accurately and without damage [7].

While affected by many factors, material handling processes in manufacturing can account for 20 to 25 percent of total production cost. However, Fragapone also states that these activities are often treated very lightly and a significant portion of costs can be traced back to material handling [8]. Material handling provides dynamism to the static elements, such as components, products, equipment. It is the activity that connects multiple assets, units, and forces of production, such as warehouse, production and assembly line, outbound, humans, and so on. It is important to think of material handling activity as part of collective processes rather than a single entity. Together with other entities of the system, the strategically and intelligently designed material handling system transforms into an interrupted and efficient flow and aims to achieve value output from such a collective system.

Overall, it is very critical for the companies to organize and design efficient material handling systems. Most of early studies have focused on designing such systems in a warehouse environment. As the top manufacturing companies have enormous and complex warehouse activities, these papers propose different decision models [2] and decision support algorithms [11] to easily keep track and optimize these activities. However, when the recent papers have been analyzed, more and more authors focus on automatization of the warehousing and other connected entities and designing the efficient intralogistics systems in the whole production floor. There have been several studies that focused on different aspects of improving material handling in intralogistics, such as equipment selection [12], analyzing different obstacles and challenges [5], investigating relations of intralogistics to the possible defect reduction and so on [6].

The organization, design, and planning principle in material handling aims to analyze the materials as well as movements to find suitable equipment. It evaluates every move, storage need, and any delay to reduce expenses, and strives to answer the questions of "why, who, what, where, when, and how? " about each action, which permits finding the most adequate solution. The equipment solution is planned using the material handling equation "Materials + Moves = Methods" [14].

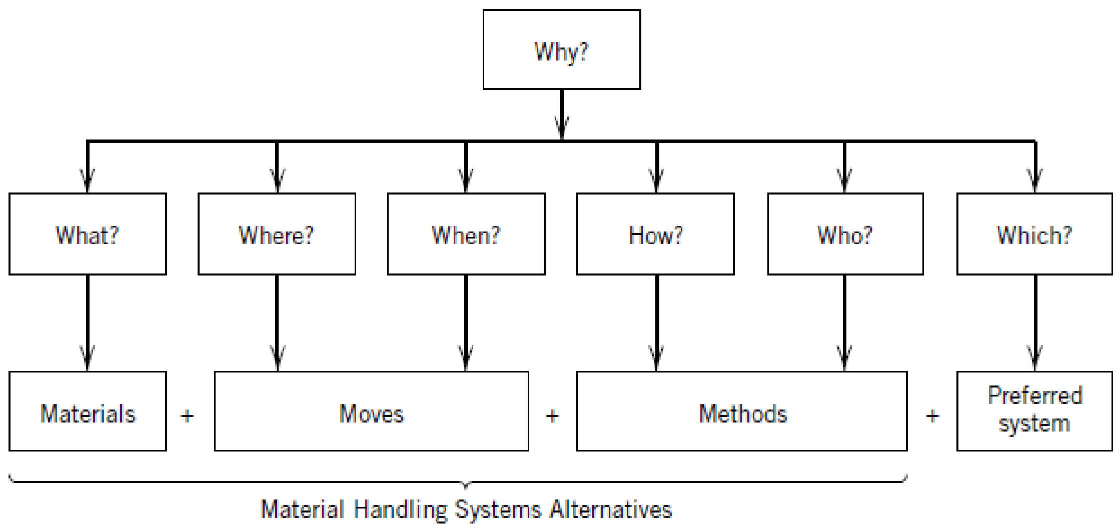

Figure 2. Material Handling Planning Principle [14]

This approach provides a rather qualitative and more thoughtful equipment selection process compared to focusing only on numerical analysis (considering, fuel costs, labor cost, etc. in [12]). It helps to identify the best suitable material handling design (flow, equipment, actors) for the layout considering that the size of layout and type of activities can be different depending on the case.

Apart from the general structure of the layout, the equipment used for sustaining the flow is also making a difference. There are different types of material handling equipment that can be integrated and used on production layout. Some common examples include:

- Forklifts: these machines lift and transfer bulky products across the industrial setting, making it simpler and more productive to move things from one place to another.

- Conveyor belts: devices that carry things from one place to another, such as from a storage area to a production line. They can be made to handle a variety of products, such as raw materials, boxes, and packages.

- Cranes: These tools are employed in building projects and large-scale manufacturing activities to lift and move big machinery or commodities.

- Pallet jacks: vehicles that can be operated manually or electrically and are used to transport palletized goods, enabling employees to move heavy loads of materials swiftly and effectively.

- Hoists: used in assembly processes or to carry items to and from storage places, these devices raise bulky objects or materials vertically.

- Autonomous Robots: Robots that can operate independently with little to no assistance from humans are called autonomous robots. Their size, functioning, mobility, and dexterity can all vary greatly [15]. In this research, the main consideration will be towards industrial mobile robots that have widespread applications around the world. There are mainly two types of industrial mobile robots used in manufacturing and production layouts for material flow: Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs)

2.3 Mobile robot competencies

2.3.1 Automated guided vehicles (AGVs)

An autonomous transport system used for horizontal material transportation is known as an automated guided vehicle (AGV). In this definition, „horizontal movement‟ is used in a sense that AGV is built to convey goods from one location to another while remaining on the defined path, without the need for any vertical movement or elevation changes. horizontal transportation refers to AGVs first appeared in 1955. Since their introduction, AGV usage has significantly increased [16]. These machines are autonomous robots that can be designed to transport items across a factory in fixed routes without the need for human intervention. They use sensors and cutting-edge control systems to avoid obstacles and travel along predetermined courses.

2.3.2 Autonomous mobile robots (AMRs)

Similar but much more superior to AGVs, these vehicles can map the production layout and operate based on optimized routes and in cooperation. AMRs function independently, which implies decentralized choices for scheduling and dynamic routing. The most typical AGVs used in industry are frequently large and need regular assistance from humans to load and unload cargo. AMRs are frequently more nimble and compact than AGVs. This suggests that AMR can access more locations and be more thoroughly integrated into workspaces or workstations, allowing for industrial flexibility and satisfying the requirements of the current production cycle [3]. AMRs are more suitable for environments that are dynamic and changing and require a greater degree of adaptability and flexibility. As autonomous robots get more advanced, setup times are getting shorter, they need less supervision, and they can collaborate with humans on tasks a cobots (collaborative robots). The advantages are growing as autonomous robots can undertake tasks that humans cannot, should not, or do not want to do around the clock with higher levels of reliability and efficiency [15].

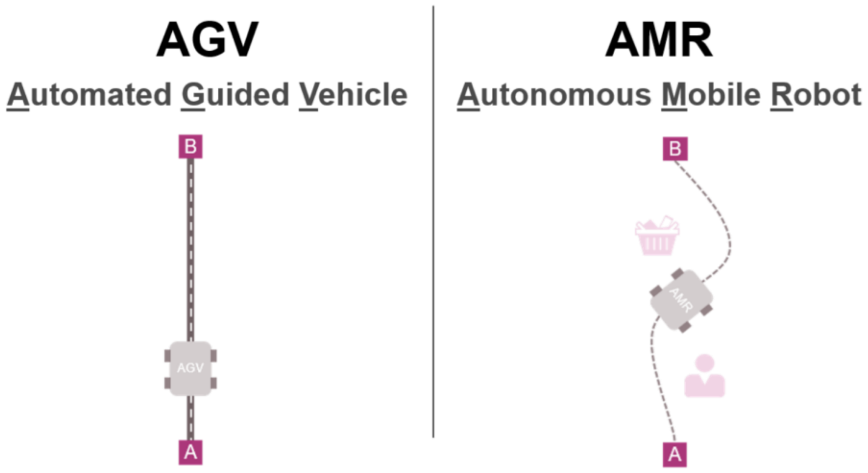

Figure 3. AGV and AMR Comparison [3]

Moreover, AMRs are decentralized entities in the system as they can make autonomous decisions compared to fully centralized AGVs in case of unplanned actions needed (such as some sudden dynamic object or human appearing on the pathway). In order to function to full extent, AGVs are required to have large and collision-free pathways, meaning that they cannot properly detect the unplanned collisions along the pathway. The main initialization input that has to be included in AMR software is the map of general layout. This includes the size of the layout and area in which AMR is "limited to operate". A robust AMR depends heavily on the quality of its map [17]. This is done mainly to avoid unnecessary non-operational parts of the layout. This is one of the most important parts of implementation [18]. It also allows the robot to have preliminary ideas about the possible borders, pathways, and obstacles along the pathway. As decentralized entities, AMRs only need inputs of starting point and the finish point when entering into the mission. These robots can find the shortest, less crowded pathways that connect the starting and finish points autonomously in collaboration with other AMRs as described in figure 4. Considering a decentralized control layer, in most cases, companies utilize multiple interconnected AMRs in the same layout, which is called a "fleet" of AMRs. There is a clear distinction in how decisions are made between AMRs and AGV systems. AMRs are able to interact and negotiate independently with AMRs, other resources, such as ERP or material handling assessment and control software, whereas AGVs depend on a central unit to make decisions regarding routing and dispatching for all vehicles, as shown in Figure 2. With a decentralized approach, there is less need for outside control because AMRs can make decisions on their own. This decentralized decision-making process aims to give AMRs the flexibility to respond quickly to shifts in demand and continuously improve their performance [7].

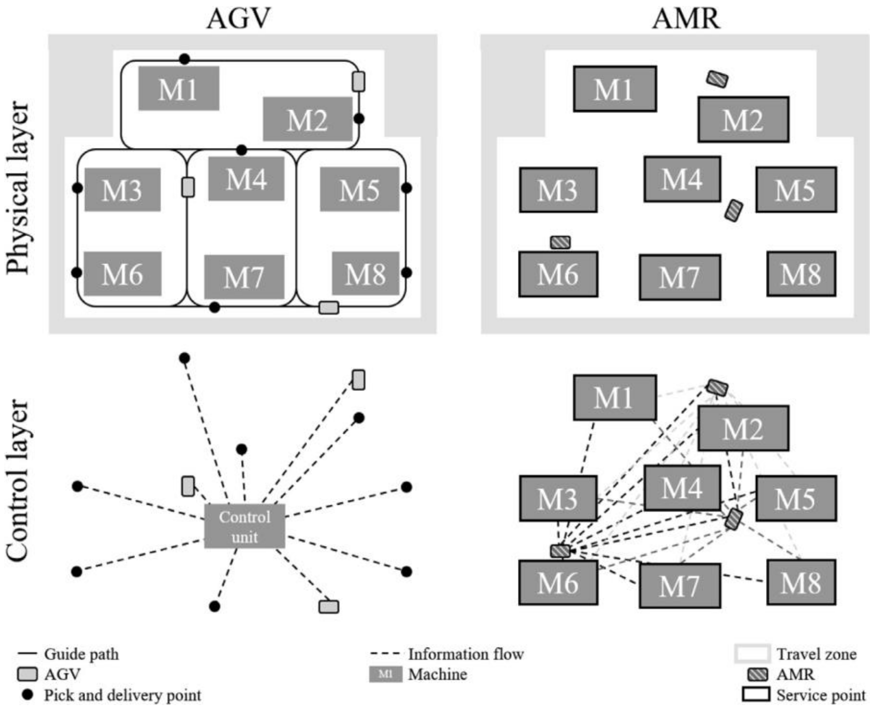

Figure 4. AMR and AGV control layers [8]

2.3.3 Hardware and software of AMRs

Focusing on the MIR 100 robot model in figure 5 from Mobile Industrial Robots (MIR) company, shown in figure 6 [19], these robots have different type of sensors to enhance the obstacle detection capability; these sensors include laser sensors, three dimensional cameras, and ultrasonic sensors. Each of these allow the robot to detect different kinds of dynamic obstacles depending on the size and position of them. More detailed technical specifications of AMR MIR100 can be found in Appendix 2.

Figure 5. MIR 100 AMR [18]

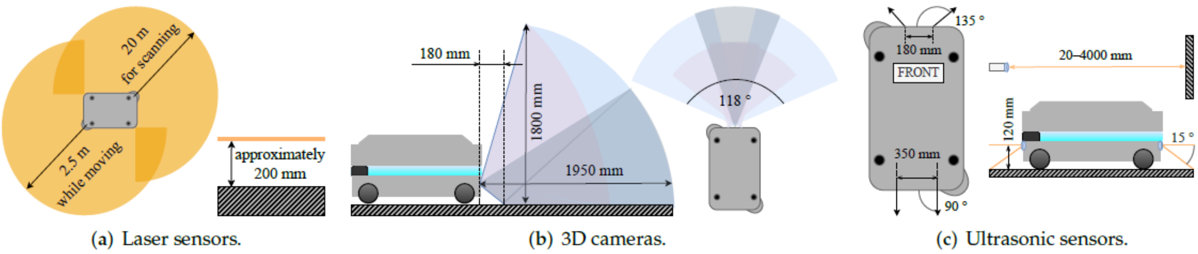

Figure 6. Types of sensors used by AMR MIR100 [19]

In order to ensure the safety of the operations with AMR, on the software algorithm side, these robots have two different software layouts: global planning system (GloPS) and local planning system (LoPS). As it was briefly mentioned before, the global planning system is responsible for creating the ideal path for robots based on the layout map, starting point, and finish point. GloPS cannot detect any unforeseen obstacles and dynamic objects. However, these obstacles are detected by the LoPS algorithm. Robots can detect, identify, avoid, make decisions in the moment of sudden obstacles with the help of LoPS layout. Hercik [18] describes the logic of these systems in a very detailed way in the paper. Figure 7 visualizes the navigation principle of AMRs.

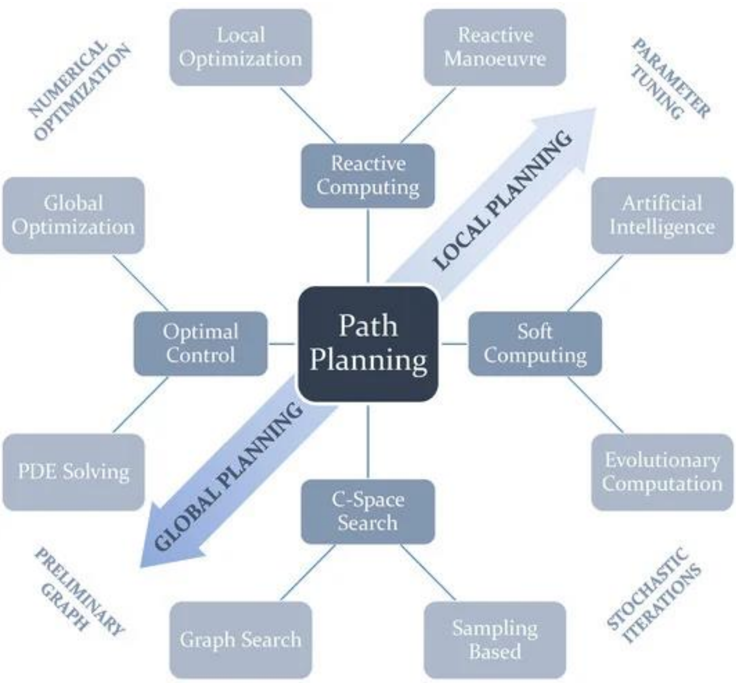

Figure 7. AMR GloPS and LoPS overview [18]

In addition to the communication capabilities between other AMRs in the same fleet, these vehicles can interact with other entities within the production system using a variety of applications and software systems, the MIR FLEET and WISE applications for the MIR100 robot are two of such examples, as described in [18].

The MIR FLEET, a web-based management tool, enables centralized control of numerous AMRs. Users can give tasks and missions to specific robots using this application, track their progress in real-time, and get alerts and notifications whenever there are problems or delays. This centralized management system makes it possible to quickly and easily make any required changes or modifications while ensuring that the AMRs are used effectively and efficiently. On the other hand, the WISE module offers digital inputs and outputs (I/O) that enable links with the mobile robot's external environment. This implies that an AMR can carry out tasks necessary for the general manufacturing process as well as communicate with other pieces of machinery or assembly lines within the production system. An AMR might be used, for instance, to transfer finished goods to a packaging and shipping area or to move raw materials from a storage area to a production line. The AMR can carry out these functions more quickly and effectively and contribute to the streamlining of the entire manufacturing process thanks to its ability to interact with other devices and systems.

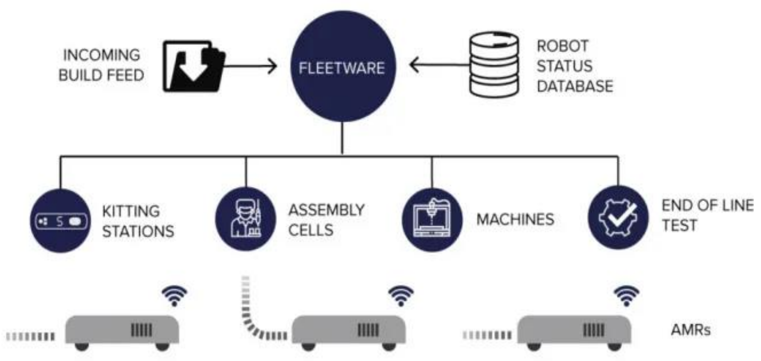

Figure 8. AMR MIR100 operation principle [20]

These software systems can potentially be used in other manufacturing layouts and have already been effectively implemented in a number of production layouts. Manufacturers can enhance their production procedures and boost their overall output and efficiency by utilizing these applications and software systems. Overall, the use of

AMRs and associated software systems offers manufacturers a substantial opportunity to streamline their processes and prosper in the competitive industry of today.

Thus, this technology is one of the main reasons behind the paradigm shift from conventional hierarchical and centralized intalogistics systems towards the autonomous intralogistics systems. In the past, fixed conveyor belts and other rigidly structured processes that needed human intervention and oversight were common features of intralogistics systems. This method was labor and time-intensive, as well as prone to mistakes and delays. Manufacturers and logistics firms have been able to automate many of these intralogistics processes, lowering the need for human intervention and increasing total efficiency, thanks to the introduction of AMRs.

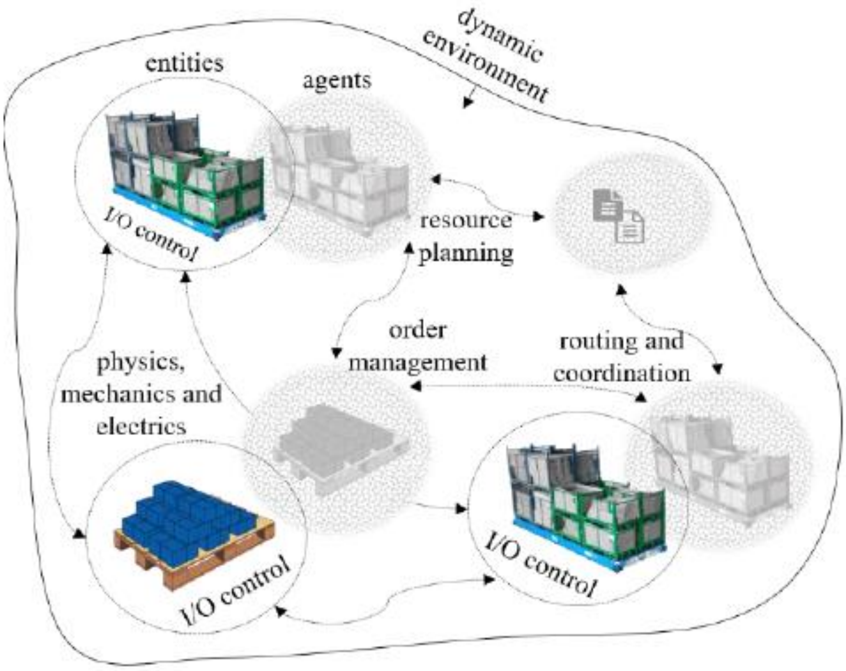

Figure 9. Links between AMR and other equipment [9]

2.3.4 MIR100 robot specifications

The detailed view on external parts of AMRs can be found in Appendix 4. It should be noted that for this research MIR100 robot has been considered as the test subject in all parts.

2.4 Automation stages

Understanding the different levels of automation that are achievable in intralogistics systems is described with the help of the five-stage automation model described by a research [9] and shown in figure 10. It is possible that higher levels of automation than those predicted by the model will be created as technology advances. But for now, the model offers a useful starting point when creating and putting into practice autonomous intralogistics systems. The model helps to define the automation level of particular production layout with all of its entities. Upon determination, it is possible to work on the improvement methods to reach the higher stages. Moreover, it may be possible to determine the preliminary investment range to reach the next goals of automation.

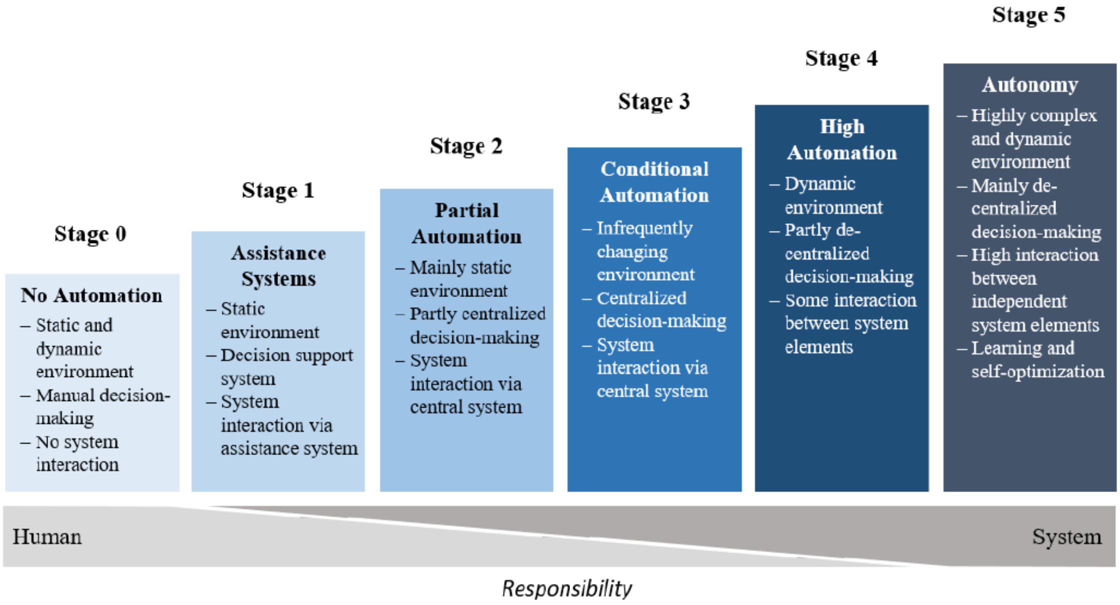

Figure 10. Automation stages [9]

Autonomous intralogistics systems can manage extremely complex and dynamic environments at Stage 5, including rapidly changing structures with multiple traffic. They have the capacity to interact with other systems and act independently in a variety of circumstances. Due to their high levels of adaptability and responsiveness, these systems are capable of optimizing their own performance using information gathered from sensors and other tracking systems. Operations in intralogistics could change as a result of this degree of automation, becoming more effective, adaptable, and receptive to shifting market demands.

Significant infrastructure and technology expenditures will be necessary for the creation of autonomous intralogistics systems. For instance, the use of autonomous systems will call for modifications to warehouse layouts, including the positioning of sensors and other tracking equipment. Additionally, new procedures for coordination and communication between various systems will be required, along with training for the operators and other staff members who will be utilizing these systems. Despite these difficulties, autonomous intralogistics systems have a lot to offer in terms of possible gains in productivity, cost savings, and safety.

2.5 AMR considerations for optimizing

AMRs have the potential to significantly increase a company's operational efficiency. However, even though the AMR involvement in material handling is a game changer, it is very important to utilize it effectively in a given company setting. The effectiveness of AMRs can be impacted by a number of things, however. Some of these elements include:

- System design:
  The AMR system design has a big impact on how effective it is. The number of robots, the size of the fleet, and the design of the warehouse or facility, among other variables, might affect how easily the AMRs can move around and carry out tasks.

- Infrastructure:
  The facility's or warehouse's infrastructure may have an impact on the effectiveness of AMR. For instance, the AMR's vision systems may not function properly in a dimly lit warehouse, which could result in mistakes or slower performance.

- Battery life:
  Since batteries power AMRs, the effectiveness of the battery may have an impact on the AMRs' performance. If the battery life is limited, the AMR would need to recharge more frequently, which would decrease its effectiveness. There have been different publications regarding improving the battery cycles of robots via wireless battery field installation proposals [13] and finding the optimal locations of chargers [21, 37] on the layout. However, these publications have mainly focused on AGVs and they do not have practical use-cases.

- Maintenance:
  To operate properly, AMRs need routine maintenance much like any other machines. The performance of AMRs might deteriorate from improper or irregular maintenance sessions. To avoid any risks, maintenance sessions have to be planned carefully considering high demand periods and AMR utilization levels.

- Systems of communication:
  AMRs frequently use WiFi or Bluetooth to connect and communicate to other robots or the Warehouse Management System (WMS). The effectiveness of the AMRs may be hampered by sluggish or unreliable communication systems.

- Human factors:
  The human elements associated in the usage of AMRs can also affect their efficacy. The AMRs, for instance, might not be utilized to their maximum capacity if staff are not instructed on how to use them properly. Incorrect AMR integration into the workflow of the organization could also result in bottlenecks or inefficiencies.

Considering these factors, it is possible to identify the weaknesses and strengths of the existing system through various tools. One of the widely used tools is process mapping.

2.6 Process mapping

A process map identifies task owners and provides expected timelines while outlining the different steps inside a process. Particularly in the context of automated intralogistics systems using AMRs, a process map is an invaluable instrument for visualizing and improving the various steps involved in a process. These maps can be used to locate process bottlenecks, redundant processes, and other areas that could use enhancement. Process maps can also help various process participants, like production managers and AMR fleet operators, communicate and work together more effectively [22].

There are several stages in the general AMR process flow in a manufacturing facility, including mission planning, dispatching, and execution. The mission planning step entails selecting the AMR that is most effective for a specific task and giving that AMR a mission. Sending the AMR to the specified place to complete the mission is known as dispatching. The AMR executes the job, which may involve picking up or delivering supplies or goods, transporting objects to new locations, or carrying out other tasks. To guarantee smooth operation, the AMR maintains communication with other devices and systems throughout the process, such as the manufacturing execution system (MES) or warehouse management system (WMS).

Below general AMR process flow illustrated in figure 11. In this case, the AMR Fleet operates in a manufacturing factory and performs different missions. As it can be visible, this is a general model how AMRs are functioning as a part of intralogistics. Considering all the advantages and high-end software solutions, AMRs can work with such flow without interruptions and human assistance.

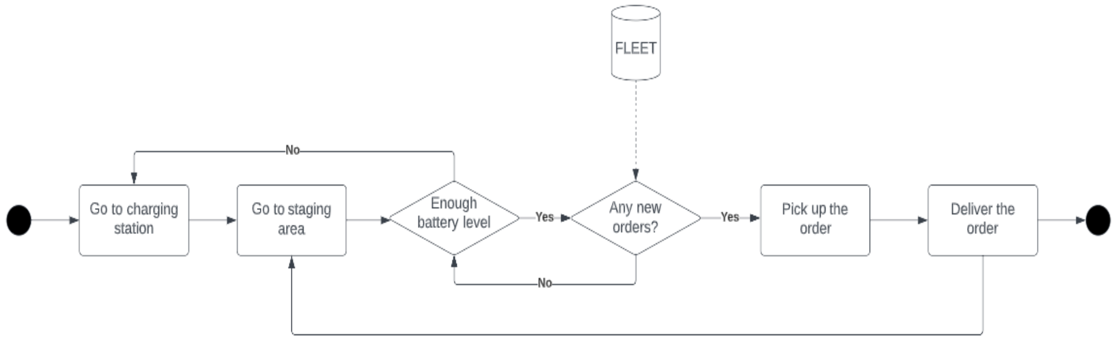

Figure 11. Generic AMR process chart

Additional stages for a more thorough flow chart might include error handling, battery monitoring and recharging, and obstacle recognition and avoidance. The safety of the AMR and any nearby human workers depends on the ability to identify and avoid obstacles. In order to ensure that the task is effectively completed, error handling entails identifying and resolving any mistakes that may occur during the mission, such as incorrect item pickup or delivery. These actions all fit together to form an effective and streamlined method for automated intralogistics using AMRs.

2.7 Performance measure

The critical quantifiable indications of progress toward an intended objective are known as key performance indicators (KPIs). KPIs establish an analytical foundation for decision making, give direction for strategic and operational improvement, and aid in concentrating attention on the most important things

KPIs can usually be measurable, quantifiable, and comparable to a predetermined target or benchmark. KPIs are used by organizations to track their performance and base decisions on end results. Organizations can assess their progress toward their objectives and spot areas for improvement by monitoring KPIs.

There are many general KPIs for production intralogistics applications. Fragapone [8] has listed multiple KPIs for evaluation of AMR application in hospital intralogistics targeting flexibility, productivity, quality and service, costs. He later breakdown all those main factors and established sub-KPIs, such as

- Number of transported items per delivery
- Ratio of value-added time to non-value-added time

- The proportion of correct and on-time deliveries
- Costs of setting up and modifying the material handling system
- Cost of single transport run
- Cost of operating and maintaining the intralogistics

In this research, author will use mainly KPIs related to delays of material delivery, changed busyness levels of robots compared with different scenarios, and cost.

2.8 Active and future state simulations

Due to the diversification and complexity of products, the demand for quicker and more adaptable production processes, and the desire to optimize logistics operations, intralogistics has become more challenging and complicated. It takes a thorough knowledge of the dynamics of the system as well as the ability to foresee and analyze the effects of changes in the system to optimize intralogistics processes. By offering a virtual representation of the intralogistics system and enabling the evaluation of various scenarios and strategies prior to their implementation in the real world, simulation modeling is a potent instrument that can assist in achieving this.

The ability to test and optimize various situations in a virtual environment without impacting the real-world system is one of the main advantages of using simulation modeling in intralogistics. This enables more effective testing that is also more affordable, as well as the early detection of possible problems. Simulation modeling, for instance, can be used to evaluate the effects of modifications to layout or routing, the effects of various product combinations, or the effects of introducing novel technologies like AMRs.

The ability to assess different strategies and compare their effectiveness is another advantage of using computer modeling in intralogistics. When dealing with complex and dynamic systems, where it is challenging to predict the results of various choices, this is especially crucial. Throughput, lead time, and resource utilization are just a few examples of the predefined parameters that can be used to evaluate various strategies and determine the best course of action. This makes it possible to guarantee that intralogistics operators make reasonable decisions that are supported by data and analysis rather than instincts or speculation.

The assessment of various scenarios and strategies is made possible by simulation modeling, which is a potent tool that can aid in the optimization of intralogistics processes by giving a virtual representation of the system. Intralogistics operators can reduce the risk of errors and downtime, save time and money, and make wise choices based on data and analysis by using simulation modeling. Simulation modeling is essential for enhancing the system's performance and ensuring its long-term viability as a result of the rising complexity and demand of intralogistics.

In this research paper, Visual Components simulation software will be used to understand the situation in the current state and to make scenarios based on the elimination of possible bottleneceks from the system.

2.9 Mathematical modeling

To establish connections between different variables in the current system, the mathematical modeling approach will be used. This will allow to establish scientific approach towards the optimization of the intralogistics problem. This method has been widely applied among different authors [23, 24] in different complexity and variability. Contrary to the very complex LP-hard problems, this paper aims to provide relatively simple modeling approach that provide the optimal solution regarding AMR allocation to different routings.

2.10 Research gaps

Application of AMRs to the intralogistics has been a very recent topic. There have been multiple papers addressing from different perspectives, such as Fragapane [3, 4, 8, 25, 26] who provided very comprehensive overview regarding AMR introduction to the hospital environment. This has been one of the quite a few papers that focused on different industry than production. Other authors also have provided insights regarding different aspects of AMRs such as scheduling, planning, battery usage, wireless charging, and so on.

According to the most rated available literature, the need for applications of AMRs into different industries are apparent. Such industries may include airline transport management systems (Airport Intralogistics), Food and Beverage industry, Agriculture, Mining, and so on. It is apparent that to function in different industries, there have to be different range of AMRs with higher speeds and higher weight load capacities. It would be better to have more research on the possible application areas and identify the real need for such AMR applications.

3. METHODOLOGY

Methodology refers to the systematic and theoretical analysis of research methods. It is concerned with the guidelines, techniques, and strategies applied in research as well as how these are used to gather and process data. Any research study needs to include a methodology section because it describes the general strategy and design of the study, including how data will be gathered, what tools will be used, how data will be analyzed, and what ethical considerations must be made. Additionally, it makes sure that research is rigorous, trustworthy, and valid and that the findings can be replicated and extrapolated to apply to other populations or situations. For producing high-quality study, a clear and well-justified methodology is essential.

For this study, mixed-method approach has been utilized as shown in figure 12. Mixed-method approach allows to produce more meaningful understanding of the research area by offering analysis from both qualitative and quantitative view [8]. Furthermore, the use of a mixed-method strategy can improve the reliability and validity of research findings because it allows for the triangulation of data from various sources, which can produce results that are more precise and reliable.

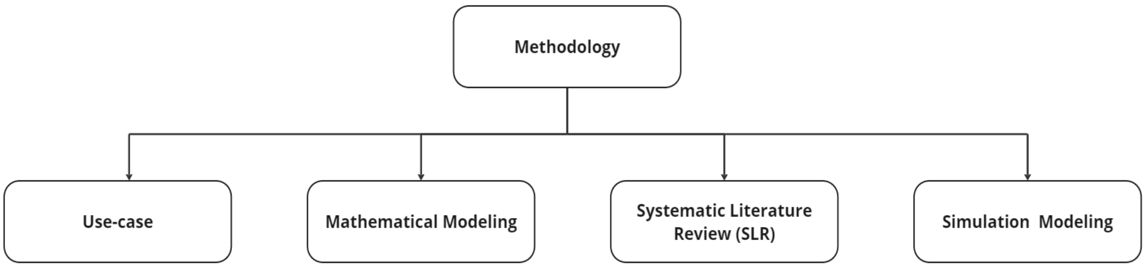

Figure 12. Research Methods

Therefore, there are four different research methods selected to study the specific research area and to be able to analyze.

3.1 Systematic Literature Review

The first method is a systematic literature review (SLR), which entails a thorough and systematic analysis of the body of literature already published on the research topic in order to pinpoint knowledge gaps and gain a better grasp of the state of the field. This approach has been used in literature review part. More than 50 papers have been analyzed and relevant ones have been thoroughly selected.

3.2 Mathematical Modeling

Mathematical modeling has been utilized to create numeric scientific approach for the research. It provides the optimal solution for the allocation of robots to the different number of routes based on the seasonal demand. With the help of the model, impact of various factors, such as addition or removal of different routes and demand variation can be simulated. There have been two models developed by the author in relation to the current research topic. One mode is utilization maximization and the other is time minimization models. The models can be visible below.

3.2.1 Mixed integer linear programming - Utilization maximization model

Sets:

$i - set\ of\ AMRs\ \in \{1 \dots n\}$

$j - set\ of\ routes\ \in \{1 \dots m\}$

Parameters:

$u_{ij} - utilization\ rate\ of\ AMR\ i\ in\ route\ j$

$c_i - capacity\ of\ AMR\ i$

$r_j -\ demand\ on\ route\ j$

$b_i - minimum\ battery\ level\ on\ AMR\ i$

$t_{ij} - usage\ of\ battery\ for\ AMR\ i\ in\ Route\ j$

$N - number\ of\ maximum\ available\ AMRs$

Decision Variables:

$$x_{ij} = \begin{cases} 1, & if\ AMR\ i\ is\ assigned\ to\ route\ j \\ 0, & otherwise \end{cases}$$

Objective Function:

$$max \sum x_{ij} \times u_{ij}$$

subject to

$$\sum x_{ij} \times c_i \geq r_j \qquad \forall j \in \{1 \dots n\} \qquad (1)$$

$$1 - \sum (x_{ij} \times t_{ji}) \geq b_i \qquad \forall i \in \{1 \dots n\} \qquad (2)$$

$$\sum x_{ij} \leq 1 \qquad \forall i \in \{1 \dots n\} \qquad (3)$$

$$\sum x_{ij} = N \qquad \forall i \in \{1 \dots n\}\ and\ \forall j \in \{1 \dots m\} \qquad (4)$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in \{1 \dots 7\}\ and\ \forall j \in \{1 \dots m\} \qquad (5)$$

$$u_{ij}, r_j, c_i, b_i, \geq 0 \qquad (6)$$

Objective function: will maximize the utilization in the system based on the most efficient allocation of AMRs into the routes.

(1): ensures that the demand in each route has been satisfied with the allocated number of AMRs.

(2): it ensures that the robots have enough battery level after completing the given task.

(3): it ensures that each has been allocated only once and there is no double work

(4): ensures that all robots in the system have been allocated.

(5): 1 if AMR i is allocated to route j, 0 otherwise.

(6): non-negativity constraint

3.3 Simulation Modeling

Scenario simulations, the third method employed in this study, entail the design and analysis of possible situations to explore potential outcomes and impacts of different variables or elements. The creation of the scenarios allows for the identification of prospective problems or opportunities that might emerge in the intralogistics system. The scenarios are based on various fictitious situations or events. The researchers can investigate several alternative approaches or techniques to deal with these problems and take use of these chances by using scenario simulations. The performance of the current intralogistics system is evaluated after scenario simulations in order to pinpoint areas for improvement. Then, several situations are used to examine and present these prospective improvement ideas. The scenarios are designed to model various intralogistics system configurations, and the key performance indicators (KPIs) that come from those simulations are examined to assess the efficacy of the suggested modifications. The researchers then offer final adjustments to the intralogistics system based on metrics that promote efficiency, productivity, and cost-effectiveness while reducing risks and disruptions. In conclusion, the use of scenario simulations offers a potent tool for investigating and optimizing various intralogistics system scenarios, enabling the development of effective and efficient strategies that can improve the general competitiveness and sustainability of the manufacturing facility.

3.4 Case Studies

The last technique is a case study, which entails a thorough analysis of a specific case or circumstance in order to discover how it functions and spot patterns and connections that might not be noticeable using other techniques. In order to simulate and predict results and behavior in the research field, a mathematical modeling approach will also be used, which entails the creation and analysis of mathematical models. By utilizing a range of research techniques, the study can take advantage of the advantages of each method and offer a thorough and well-rounded analysis of the research field. The findings can be used to guide policy and practice in the field and will enable a more accurate and nuanced understanding of the subject. For the current research, use-case from Fragapone's [8] and Hendrick's [27] studies have studies in a detailed way. The author mainly focused on the hospital intralogistics improvements, however, the main components of the research have been very similar.

3.5 Methodology Overview

The general framework has been given in the figure 14. As it is illustrated, the whole project is consisted of three main parts: Design and Planning, Analysis, and Verification. The research study will only focus on the first two categories due to time-related limitations of the thesis study established by university.

In the Design and Planning part, the study need to be conducted in order to familiarize and deepen the knowledge regarding general principles of material handling and AMRs in manufacturing industry setting. Multiple case studies and SLR should be completed in order to grasp the general principles and understanding. The outcome related to the general structure of the thesis, such as formulating research questions, problem statement, and targets are esstablished.

In the analysis part, more in depth research in practical sense need to be completed and data have to be collected. In many cases, collected data need to be cleaned and structured in order to be able to create a pattern and meaning out of data. Once the processing done, ready data should be fed into mathematical and simulation models. Continuous refinement approach should be used in order to link and enhance the effectiveness of simulation models. Once the simulation model is robust enough, current state and proposed scenario models should be simulated and performance measure need to be taken with the help of KPIs. Results should be compared and notable changes should be highlighted.

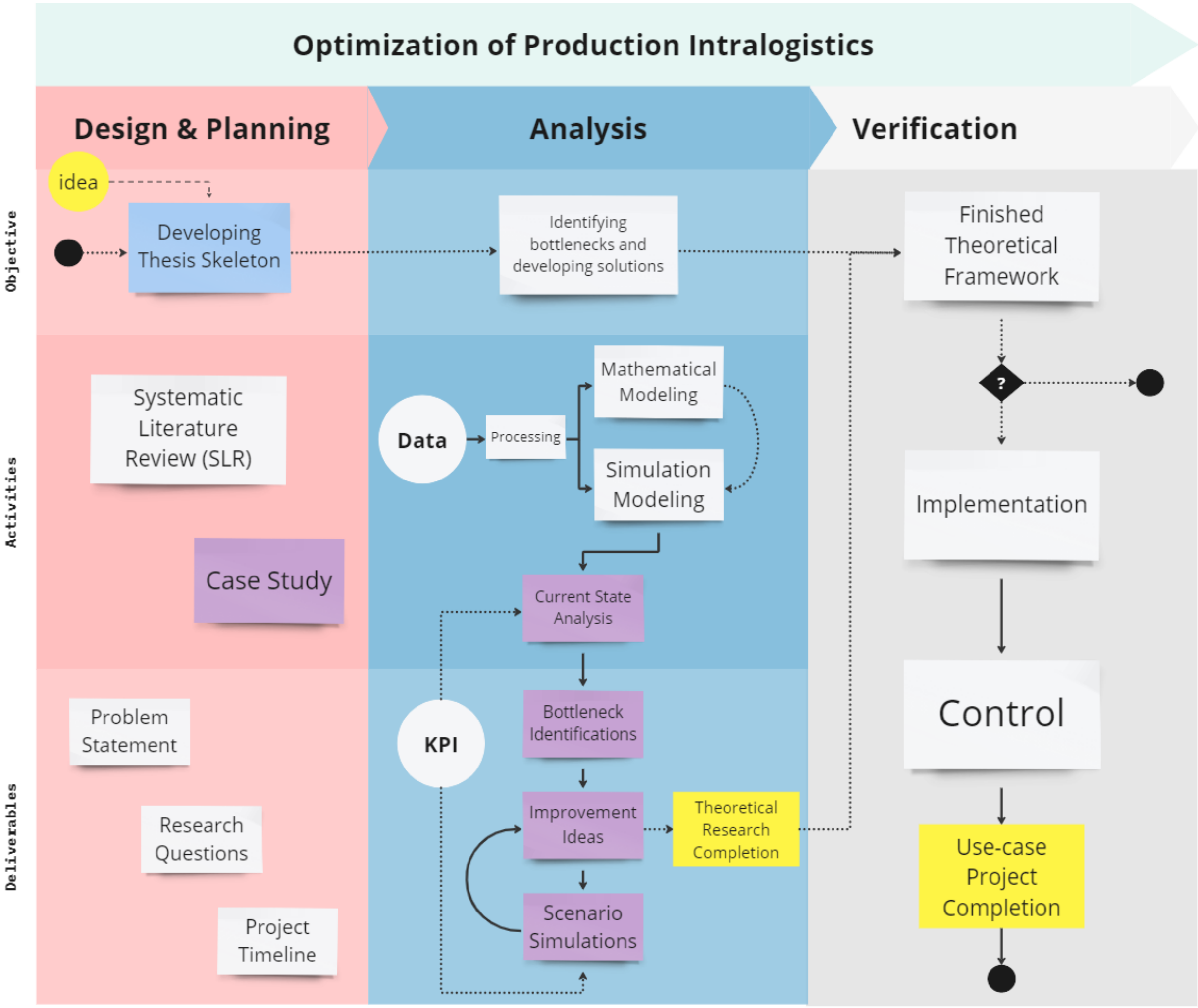

Figure 13. Optimization of Production Intralogistics Methodology

In verification part, selected scenarios should be implemented and real time measures should be ensured. After implementation, maintenance and control should be provided in order to sustain the system.

4. USE-CASE

This chapter will discuss company intralogistics in multiple directions. First, current state overview will be presented. The problems will discussed and base for improvements will be provided. Problematic areas will be identified. Simulation modeling will be used utilized to demonstrate the performance measure. In the later parts, possible improvement ideas will be presented and multiple scenarios will be simulated to validate those ideas. Lastly, discussions regarding maintenance and control will be made. Alongside this flow of information, research questions will be answered and thesis will be finalized.

4.1 Current state analysis

In this section, current state of the material handling processes alongside with production intralogistics will be analyzed. Problematic areas will be identified and relative performance measures will be determined. In this part, there will be 3 different sections provided; AMR routes, manual labor in AMR tasks, and standardization problems will be discussed. At the end, current state simulation will be done and KPIs will be measured. The aim of this chapter is to identify the areas where the KPIs are low and further improvements needed.

Referring to the general material handling procedures in the given company circumstances, multiple stakeholders from different activity groups are involved. Stakeholders included from Production Planning, Warehousing, Kitting, Transportation, and Assembly line workers are the main ones. Figure 15 shows the general material handling flow on the production layout. The flowchart illustrates the current situation. Bigger version is available in Appendix 1. The flow chart allows the viewers to have general idea about the processes at first. Potential improvement parts can be derived from the flow.

Some problematic areas in the current flow are illustrated with red boxes in the process chart:

1) In warehouse level, finding and deciding the usage of trolley has been done in fully manual way of work based on human knowledge without established procedure. This causes delays in the flow as every time there need to be a search done among more than 18 types and overall hundreds of available trolleys.

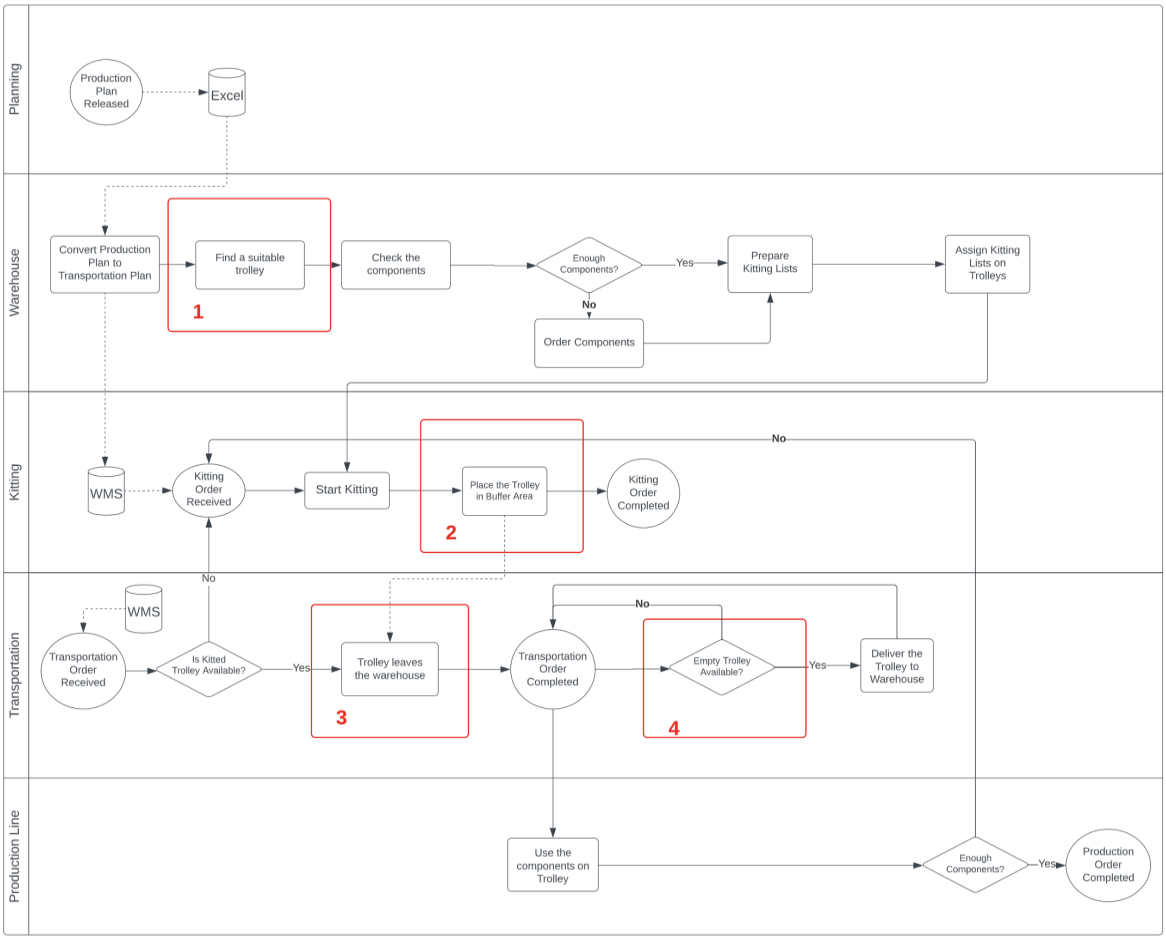

Figure 14. Material handling procedure

2) In kitting phase, after the kitting process completed, worker moves the trolley to the buffer area where the trolley stays idle until transportation worker notices and starts to move it to the production line.

3) The transportation phase is rather general and it is mainly illustrated considering the human transportation worker. There are multiple problematic areas in the flow. Firstly, the order has been recorded as complete once the trolley leaves the warehouse area. This does not allow to monitor if the trolley has reached its correct final destination or not, considering that there are multiple different assembly line postions where the trolleys need to be delivered.

4) Upon delivering the trolley, the assembly line workers start to utilize the components on it and once finished, they leave it to on the layout. The trolley is moved back to the warehouse only when the tronsportation worker brings another loaded trolley. This creates a space problem and does not allow to have organized way of work. There is no automatic trigger system for the warehouse to know if there are any empty trolleys idling on the production line. This causes

the trolleys to wait near the line on average up to 3 hours. In the figure 16, this KPI has been illustrated for only one type of trolley. If we avoid the outliers in the whole data (above 3000 minutes), still the time spent near the assembly line has been quite high in many occasions compared to suggested threshold limit, which is 65 minutes. This data is more or less the same for the other trolley types. Such problems need to be avoided with the intgration of smart systems for the trolley management. Details will be discussed in improvement part.

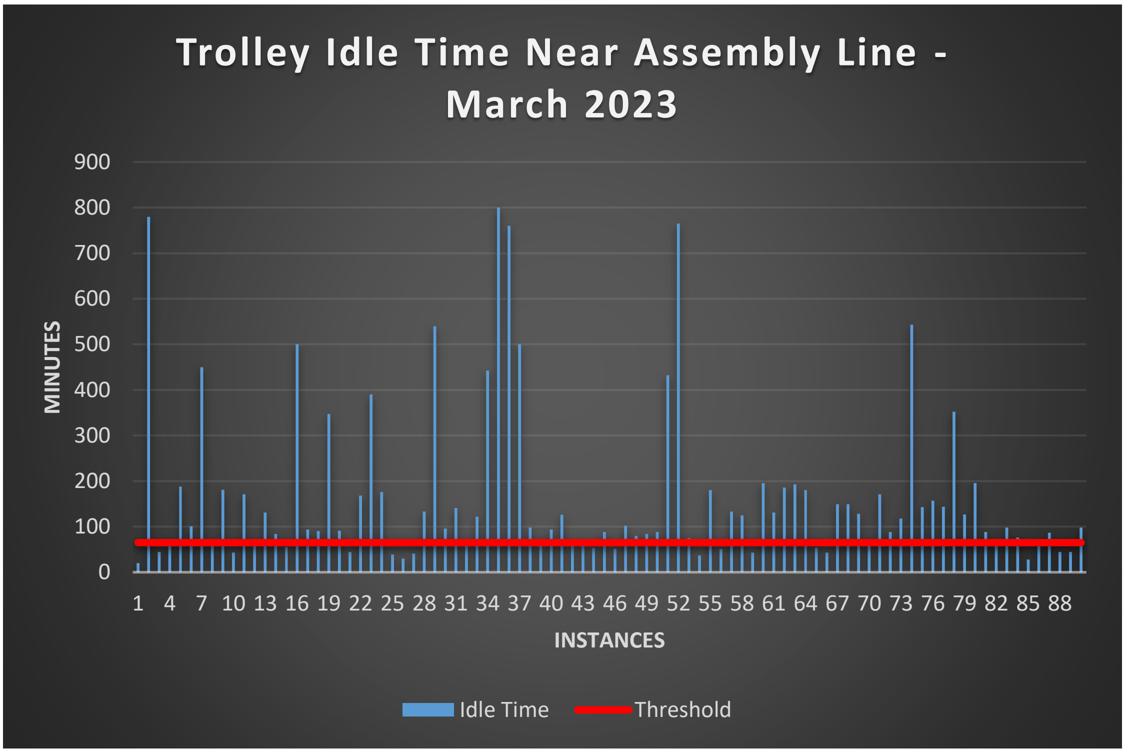

Figure 15. Idle trolley instances and times

Lastly, it is important to have automation processes involved in the material handling process as much as possible. In the current process, human trigger is needed to send transport order to WMS as in figure 17. Kitting workers will press the button on the tablet to inform WMS that kitting process completed and the trolley is ready and waiting for transportation. There should be some automation added into this process to remove manual work of order triggering.

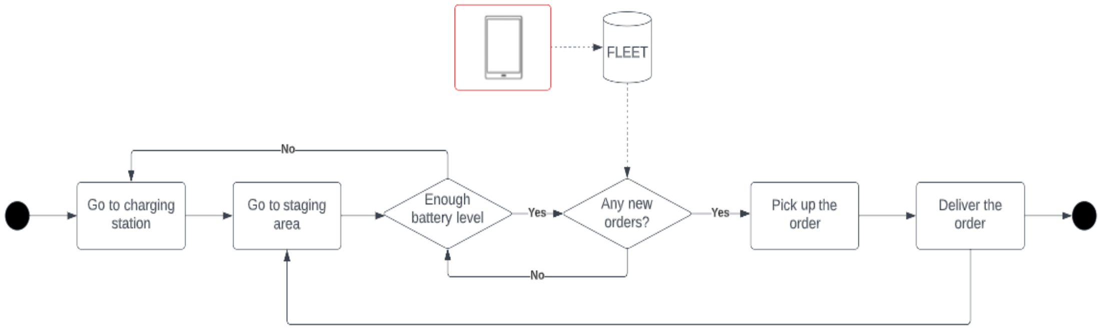

Figure 16. Current AMR flow

All of the above mentioned problems together contribute to the state of production intralogistics. As it was mentioned in figure 1, efficient material handling is most important part of the production intralogistics. Efficiency of the system allows for better conditions for the AMRs and their usage. However, it is better to approach to solve these problems starting from detailed view of each process. In the next few sections, the author will analyze other sub-parts of the overall production intralogistics system.

4.1.1 AMR pathways

The aim of this sub-section is to show the general factory layout with the emphasis on the AMR routes. The factory is consisted of multiple different halls organized based on the production flow of different products. This layout is quite dynamic as it is subject to change up to few times a year usually depending on the long-term demand forecast levels some other requirements, such as addition or removal of new equipment. It is important to reduce the complexity of material handling processes especially in regard to high-runner products that are essential part of company's success in the long-term period. Dynamic layout adds another challenge to the current research by bringing the last third question which is related to how the organization of robust AMR flow should be made in order to reduce the effect of changes on the operations of AMRs.

In the current setting, AMR robots are operational continuously during the day. There are 7 AMR robots in the current layout. These robots are performing material handling operations in total of 4 different routes with 4 final destinations on the routes. In figure 18, all routes where the robots can operate have been described. The question might arise as it was described in previous parts that AMRs does not need fixed routes in order to operate. It is important to understand fundamental difference between AGV and AMRs clearly. For AGVs, humans are selecting which route exactly to follow in order to fulfill a task. Without this, they are non-operational. However, for AMRs, humans only determine the area in the map without a need to specifically determine the routes. AMRs then „learn" all routes and determines the best among them to fulfill a task. „Limiting" the AMR movement with assigned routes is quite common and it is described in multiple papers questioning as how much decentralization should be given to AMRs in their daily operations. Determining the optimal decentralization level is very hard mathematical problem and usually achieving feasible solution is considered good enough solution. Fragapone [7] has listed many different papers in his research agenda regarding this topic

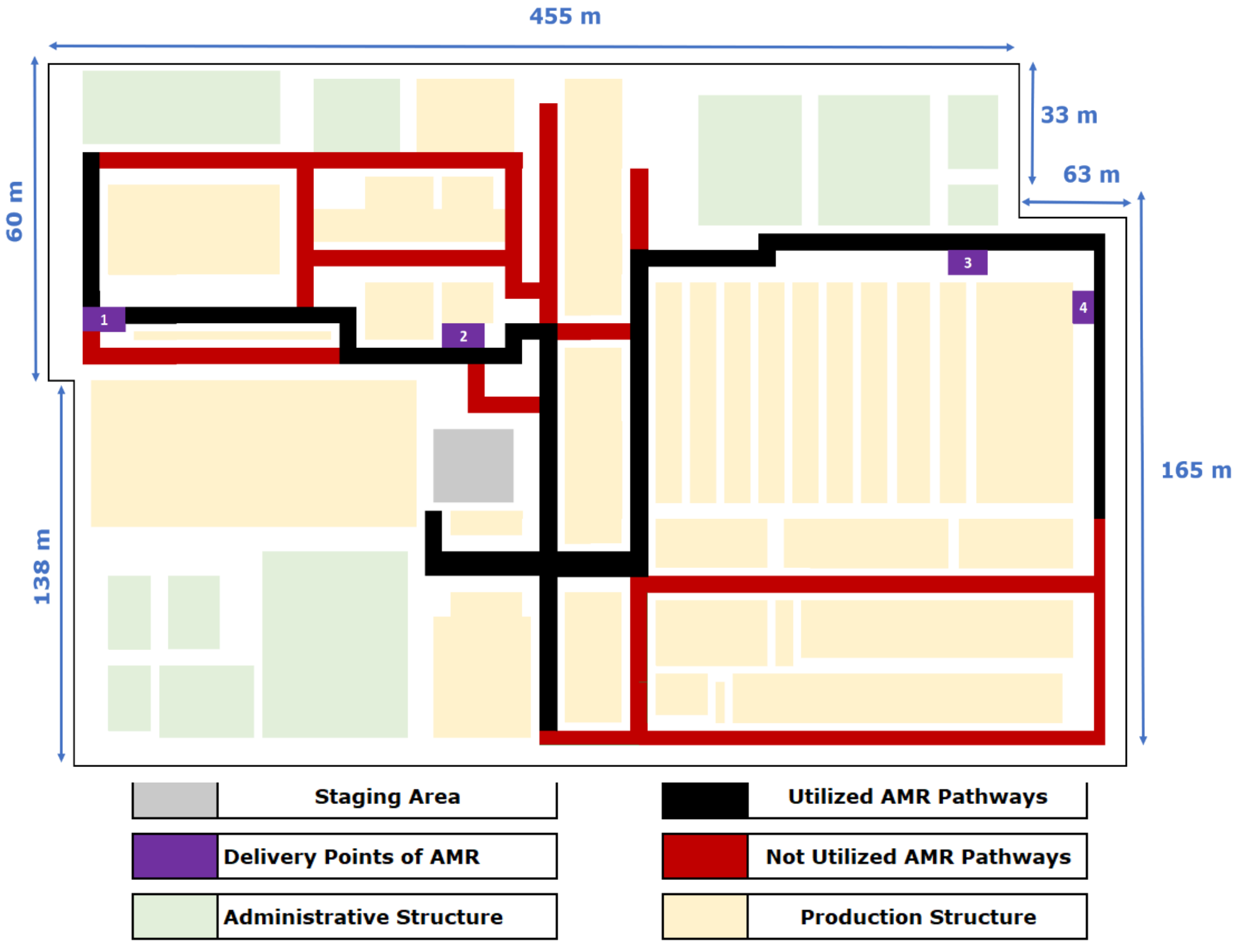

Figure 17. AMR pathways in the factory

It is important for the AMR automation and planning engineers to provide feasible level of decentralization to these robots in terms of their space of movement due to the reason that not giving such guidance will reduce the productivity of robots greatly. As an example, MIR added the different option in the software to guide the AMR in specific areas. As it can be seen in figure 19, the red area is forbidden, green area is preferred, and yellow area is where the robot should operate while making sound.

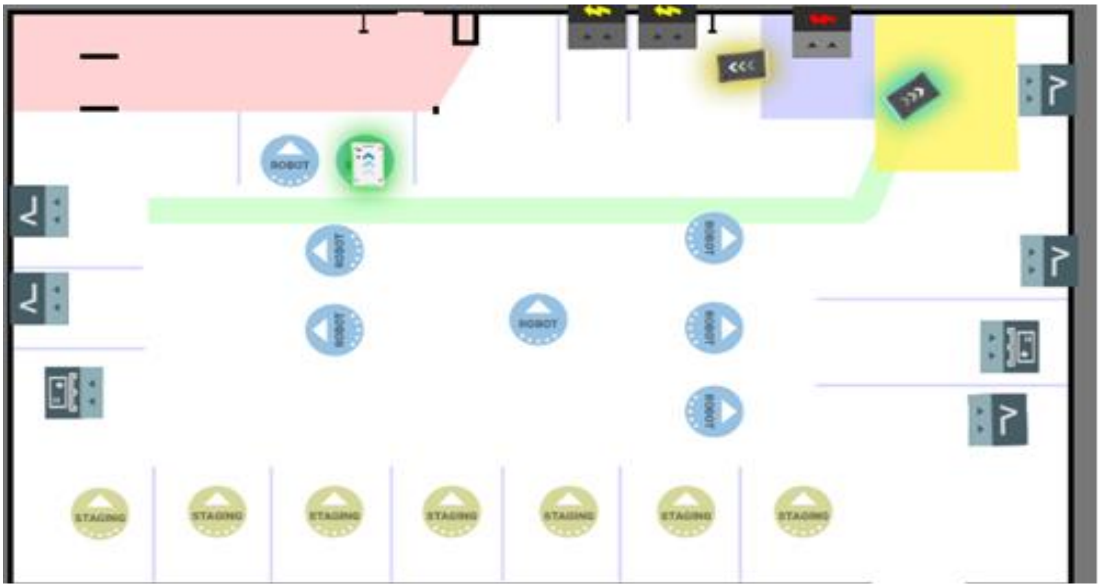

Figure 18. MIR AMR mapping view [19]

Referring back to figure 20, it is apparent that only some parts of the potential routes have been utilized by the robots. Non-utilized pathways have been illustrated with dark red color on the layout map. It is essential to note that these unused paths may offer opportunities for improvement in the future. A further examination of the underutilized channels might reveal information about the performance of the system as a whole and point out potential areas for improvement. Some of the reasons are related to uneven surfaces and narrow corridors. Narrow corridors can also be resulted from having production equipment placed on the paths as well. There should certain guidelines and standardization actions in order to remove such problems. Removal of such problems will allow for addition of different unutilized paths and therefore increase of AMR utilization rates.

There are other different topics to investigate regarding the reasons behind the zero utilization of the red pathways. These include usage of manual transport, lack of standardizations for higher AMR utility, ignorance of production areas where less production output is available and so on.

4.1.2 Manual labor in material handling

Manual labor is used in many manufacturing layouts. This is the main obstacle to reach the full automation level for any facility. Most of the times, companies stand still on 4th Automation level (check figure 10) for a long time due to being unable to remove humans completely from certain operations.

In this use-case, in the figure 16, it can also be seen from the map that around those red pathways, there are different production facilities, such as assembly lines, testing areas, and so on. This clearly means that there are different material flows available to those areas without AMR usage. It is not difficult to figure out that the transportation is realized by manual labor, more specifically by transportation workers. There are a few transportation workers available every shift in the factory in order to transport the available kitted trolleys to the different positions of different assembly lines. Considering many different product types the company produces, there are more than 10 different assembly lines in the current layout. However, AMRs are only assigned to 4 different routes. In other words, with the current level of assignment, it is not possible for the factory to fully utilize the available AMRs in all of the material handling activities. That is why, in this paper, the author will investigate the ways of improving this situation to increase the utilization rates of AMRs.

4.1.3 Standardization and specifications for AMR planning and control

General International Standards

These safety requirements are important because driverless autonomous robots have the potential to harm or injure individuals and assets if they are not developed, manufactured, and used in a safe manner [28]. These robots must be built to manage a variety of situations while protecting the safety of humans and the environment because they operate in dynamic and unexpected surroundings.

AMRs must be designed, built, and operated in accordance with the safety standards listed in Table 1 in order to be trustworthy and safe. Manufacturers can make sure that their robots are made with safety and certain performance needs in mind by adhering to these standards.

Table 1. Main standardizations for MIR100 AMRs

Electromagnetic Compatibility (EMC) part 6.2 [29]	EVS-EN IEC 61000-6-2:2019
Electromagnetic Compatibility (EMC) part 6.4 [30]	EVS-EN IEC 61000-6-4:2019
Industrial trucks - Safety requirements and verification - Part 4 [31]	EVS-EN ISO 3691-4:2020
Industrial Mobile Robots - Safety Requirements - Part 1 [32]	ANSI/RIA R15.08-1-2020
Guided Industrial Vehicles [33]	ANSI/ITSDF B56.5-2019

Layout specifications

Most of the reasons are related to the fact that standardization levels in some parts of the layout do not meet AMR requirements. Non-standard actions creates potential danger for the movement of AMRs. It is obvious that AMRs have been designed to be as compact as possible with high level of intelligence. They are fitting most of the corridors with ease and can avoid accidents with the sensors and intelligence systems they have been equipped. The specifications for the environmentis listed in below table 2. More detailed view can be found under Appendix 2.

Table 2. Environmental specifications MIR100

Operational corridor width	With default setup: 1 000 mm | 39.4 in
Maximum incline/decline	± 5% at 0.5 m/s
Ambient temperature range, operation	5–40°C | 41–104°F
Humidity	10–95% non-condensing
Floor conditions	No water, no oil, no dirt

However, in the current company setting, AMRs are used for carrying trolleys from one point to another. Considering the current corridor widths, almost all of the paths are more than 1000 mm in width. However, there is a missing consideration here. It is very important to consider the trolley width especially when it is more than the AMR width. Moreover, 1000 mm in width creates another bottleneck queue situation as it only allows one-way transport along the path just like in figure 20. In other words, in case of high demand in one of such routes, only one AMR robot will be able to transport components at a given time. This will create a bottleneck.

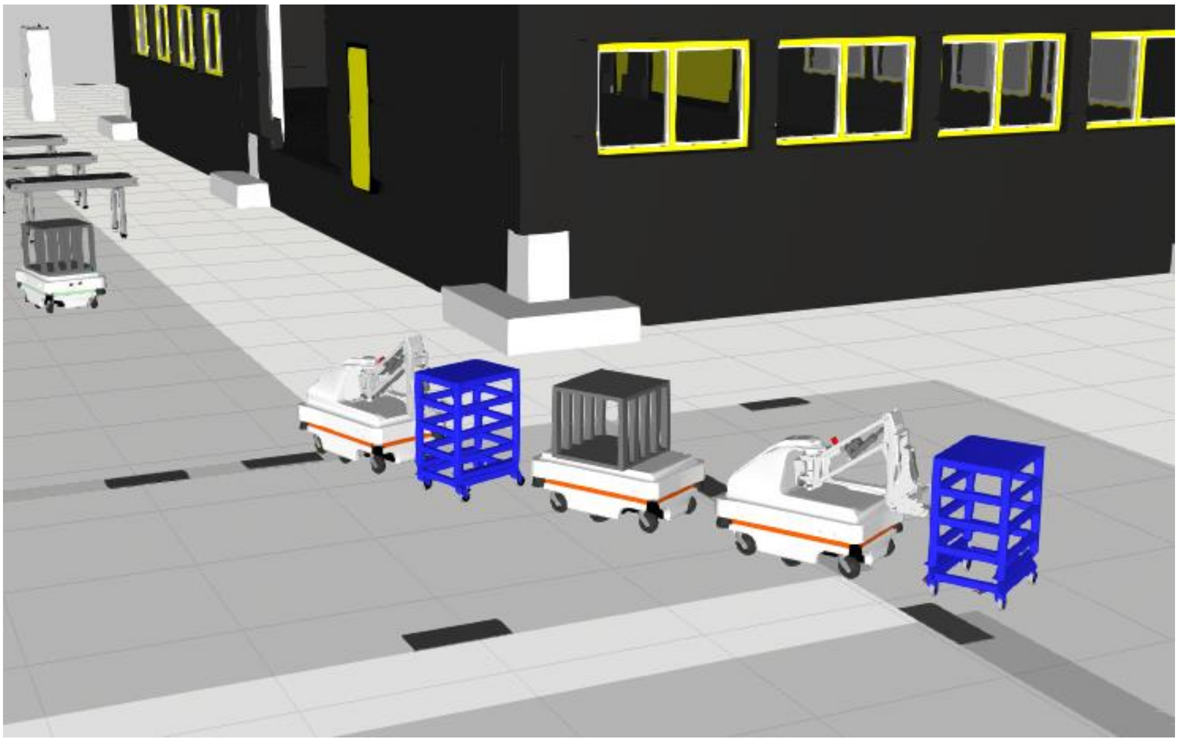

Figure 19. Bottleneck situation due to one-way narrow path[2]

Trolley standardization problem

In the current production layout, there are around 20 types of trolleys. These trolleys have been specifically designed to transport different types of components that used for various types of products. As the demand for old products gradually maturing, dedicated trolleys also start to become underutilized. However, AMR-compatible trolleys have been engineered only after the AMR introduction on the layout few years ago. According to the most recent data, only half of the trolleys are AMR-compatible. It is apparent that to add new routes and to make AMRs much more flexible, number of AMR-compatible trolley should be increased. This will allow AMRs to be able to transport new component groups to different production lines and, therefore, will increase the utilization.

4.1.4 Current state simulation

Considering the mentioned problematic areas, it is assumed that the current utilization levels of AMRs and overall efficiency of production intralogistics will not be high.

[2] Illustration has been taken from simulation run.

Simulation study will allow the users to visualize the predicted problems in the setting. Given the correct data, the simulation will generate close to real life analysis.

General data processing model for all simulations

The data for the simulation model have been collected from WMS database. For the given product demand for all types of currently available products, the database provided the number of needed trolley types transporting to different positions of production line. There is no automated system for generation of trolley demand and therefore a data processing model is needed to simulate existing and upcoming scenario simulations. Such model has been developed by the author in the metadata. The general working principle of the model has been provided in the below figure 21. The model removes the complexity from the data gathering process and allows the user to collect data independently once the demand number are known. User does not need to get input from warehouse to calculate the needed trolley numbers for each type and position in the production line.

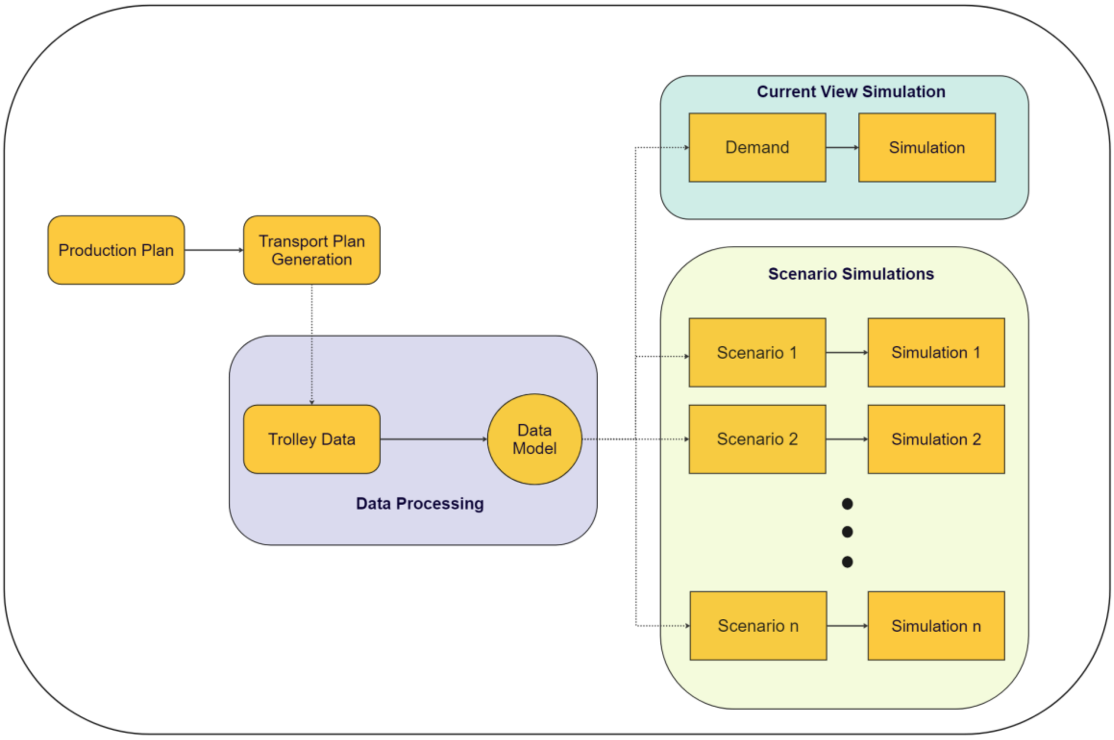

Figure 20. Data processing model diagram

Mathematical model

In this paper, mathematical model will provide efficient solution for the allocation of AMRs into available number of routes. In the current setting, there are 7 AMRs and 4 routes available. Once there are new routes added, model will provide solution how to allocate available AMRs into new routes for more efficient utilization.

Detailed usage of mathematical modelling and code can be found in Scenario #1 chapter.

Simulation

The input data for simulation will be based on the weekly production volumes of different products shown in table 3. In this research, only volume products will be considered without paying attention to the NPI products. Here is the volume data for the given week:

Table 3. Weekly volume production plan

Product	Weekly Plan (in units)
PRODUCT 1 V1	518
PRODUCT 2 V1	416
PRODUCT 2 V2	346
PRODUCT 1 V2	269
PRODUCT 2 V3	151
PRODUCT 3 V1	151
PRODUCT 3 V2	33
PRODUCT 2 V4	9

With the given input, the data model creates a trolley need data. The production operates 24 hours a day with 2 shifts each day. Here are the basic formulas to calculate the trolley need:

$$\boldsymbol{Trolley\ need\ to\ produce\ 1\ pcs\ Product} = \frac{\mathbf{1}}{\boldsymbol{Number\ of\ components\ on\ one\ trolley}}$$

Let's call above formula as (F1). It is important to consider that there is usually more than one component on trolley transferred to production line to produce certain product. As an example, if there are 6 components on each transported trolley to produce Product A, then to produce 1 pc Product A, there will be a need for 1/6 = 0,167 pcs trolleys. This method allows to systemize the trolley calculations for any given demand.

$$\boldsymbol{Total\ Needed\ Trolleys\ in\ a\ Week\ for\ Product\ A} = \textbf{Weekly Plan for Product A} \times (\mathbf{F1})$$

Let's call the above formula as (F2). By knowing weekly trolley need, it is also possible to know the shiftly needs. Depending on the production planning principle (maximizing the shift plan and therefore finishing early or planning average level each shift), number of trolleys can be calculated based on ceiling principle.

By considering the above calculation formulas and other factors, below table shows the trolley data generated by the model:

Table 4. Trolley need based on weekly plan

Product	Trolley Type	Position	Weekly Plan (in units)	Total Needed Trolleys in a week (in units)	number of trolleys per Shift (in units)
PRODUCT 2 V3	TYPE A	Position 1	151	13	1
PRODUCT 2 V3	TYPE A	Position 2	151	13	1
PRODUCT 2 V3	TYPE B	Position 3	151	9	1
PRODUCT 2 V3	TYPE C	Position 4	151	26	2
PRODUCT 2 V1	TYPE A	Position 1	416	35	3
PRODUCT 2 V1	TYPE D	Position 2	416	12	1
PRODUCT 2 V1	TYPE D	Position 3	416	18	2
PRODUCT 2 V1	TYPE A	Position 4	416	35	3
PRODUCT 2 V4	TYPE A	Position 1	9	1	1
PRODUCT 2 V4	TYPE A	Position 2	9	1	1
PRODUCT 2 V4	TYPE B	Position 3	9	1	1
PRODUCT 2 V4	TYPE C	Position 4	9	2	1
PRODUCT 2 V2	TYPE A	Position 1	346	29	3
PRODUCT 2 V2	TYPE A	Position 2	346	10	1
PRODUCT 2 V2	TYPE A	Position 3	346	15	2
PRODUCT 2 V2	TYPE A	Position 4	346	29	3
PRODUCT 1 V2	TYPE C	Position 1	269	27	2
PRODUCT 1 V2	TYPE E	Position 2	269	3	1
PRODUCT 1 V2	TYPE F	Position 3	269	12	1
PRODUCT 1 V2	TYPE E	Position 4	269	34	3
PRODUCT 1 V1	TYPE C	Position 1	518	52	4
PRODUCT 1 V1	TYPE E	Position 2	518	5	1
PRODUCT 1 V1	TYPE F	Position 3	518	23	2
PRODUCT 1 V1	TYPE E	Position 4	518	65	5
PRODUCT 3 V2	TYPE I	Position 1	33	33	3
PRODUCT 3 V2	TYPE G	Position 2	33	3	1
PRODUCT 3 V2	TYPE H	Position 3	33	5	1
PRODUCT 3 V2	TYPE H	Position 4	33	2	1
PRODUCT 3 V1	TYPE I	Position 1	151	151	11
PRODUCT 3 V1	TYPE G	Position 2	151	13	1
PRODUCT 3 V1	TYPE H	Position 3	151	13	1
PRODUCT 3 V1	TYPE H	Position 4	151	13	1

Taking the above data, we can calculate the number of trolleys need to be transported in each route in the given shift. Considering that in the current scenario there are total of 4 different final destinations (or four different routes), here is the number of types of trolleys need to be transported in each route.

Table 5. Number of trolley types needed

Trolleys	Total Need Weekly (in units)	Total Need Shiftly (in units)	AMR Compatible
TYPE A	181	19	yes
TYPE B	27	4	no
TYPE C	186	15	yes
TYPE D	30	3	yes
TYPE F	35	3	yes
TYPE I	184	14	no
TYPE G	16	2	yes
TYPE H	33	4	no
TYPE E	107	10	yes

As it can be seen from the above table, based on the randomly selected weekly production plan, out of total 64 trolley movements, only 42 of them can be transported by AMRs. By utilizing the route info and trolley type info, it is also possible to propose below table, which shows the route and trolley type relations.

Table 6. Simulation input data

Routes	Trolley Types	Count per shift (in units)
Delivery Point 3 – Line A	TYPE E	10
Delivery Point 4 – Line B	TYPE C	15
Delivery Point 4 – Line B	TYPE G	2
Delivery Point 2 – Line C	TYPE D	3
Delivery Point 2 – Line C	TYPE A	19
Delivery Point 2 – Line C	TYPE F	3
Delivery Point 1 – Line N	Built-in trolley on AMR	25

Table 7. Current state simulation

Current State Simulation Settings	
Energy Management	Charging up to 90% once battery level drops to 60%
Pathways	70% of pathways one-way, 30% two-way
Demands Level	Low
Time	12 hours
Layout	Existing layout model
AMR	Existing allocation

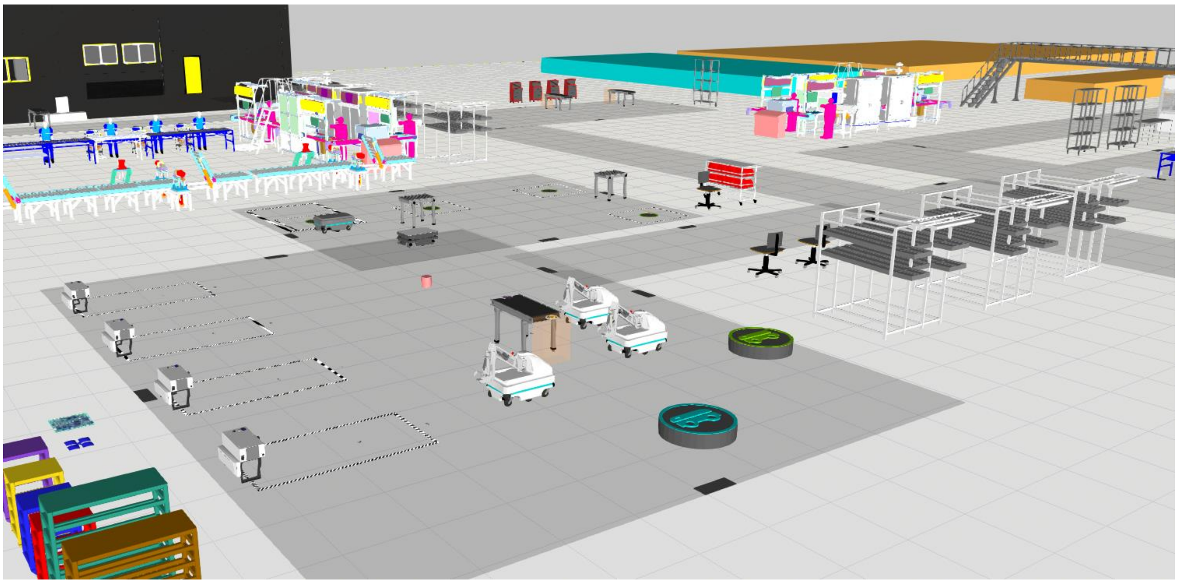

Figure 21. Simulation layout view 1

Figure 22. Simulation layout view 2

Overall simulation layout view can be seen from figures 22 and 23. For the simulation, different set of robots have been used to make it more generalized. After inputting the data into the simulation with the current setting and the discussed problems, simulation has been run for 12 hours to represent 1 shift in real time. Statistics have been collected. As it can be seen from figure 24, the utilization levels of the robots have been quite low as all robots are under 10 per cent rate. Moreover, other statistics have collected and presented in Appendix 3.

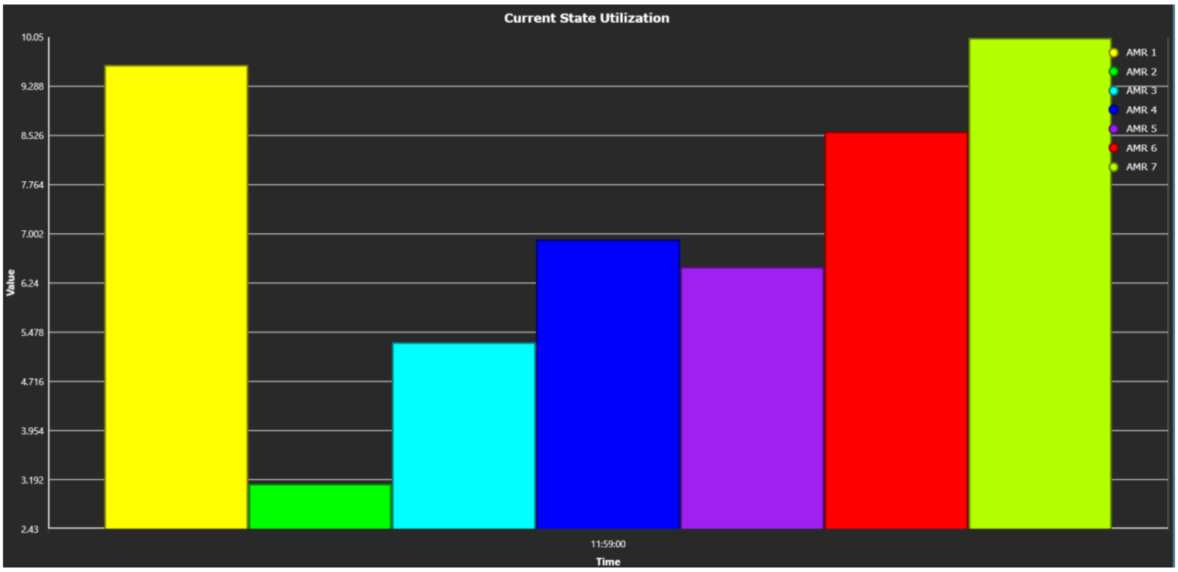

Figure 23. Utilization rates of robots: bar chart view

As it can be briefly seen from figures, there are disbalance happening in the path planning as not all the paths have been utilized in the same level. This can be observed from the distance travelled and batches delivered dashboards.

In the next section, possible improvement areas will be discussed and analysed. After that, credibility of theoretical analysis will be simulated and the same statistics from old and new states will be compared. Improvements in the numbers will be presented.

4.2 Exploring potential improvements

In this chapter, potential ideas for optimization of mnaufacturing intralogistics will be discussed. As shown in the below figure 25, the scope of the improvements will mainly focus on 3 segments: technical enhancements, trolleys, and pathways.

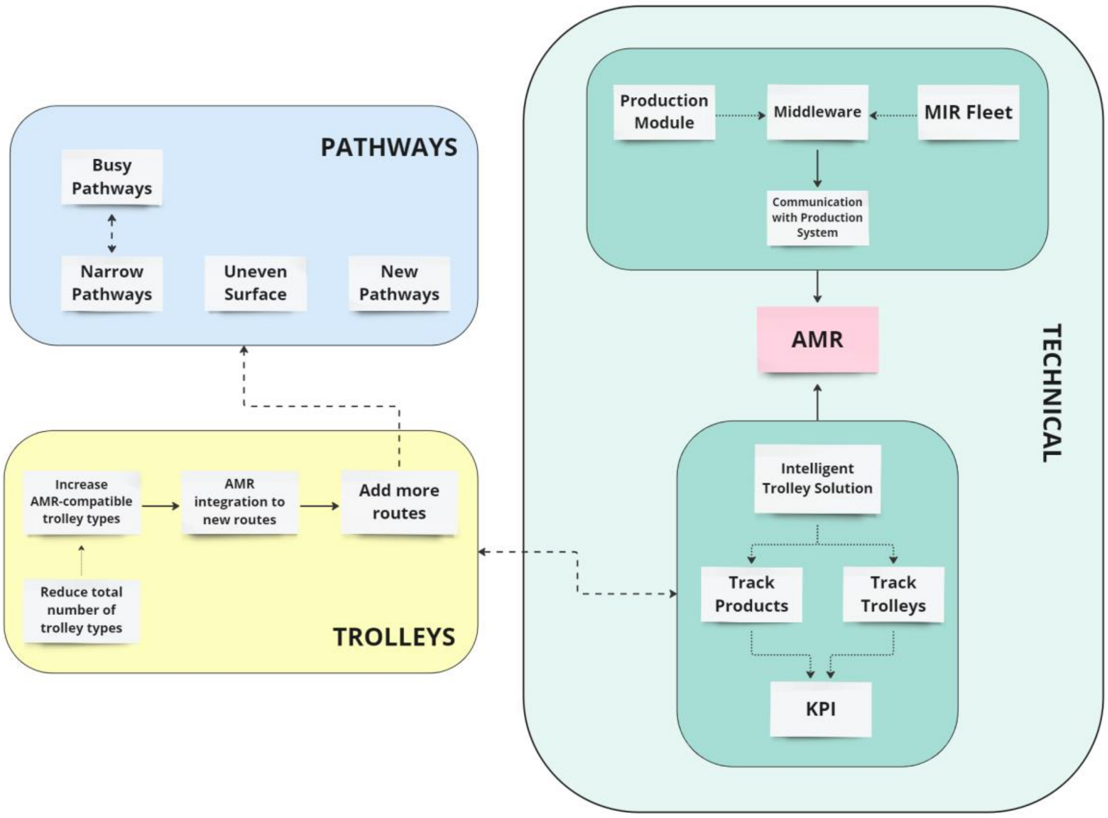

Figure 24. Improvements scope

4.2.1 Technical enhancements

Using AMRs to fully automate the material handling procedures has a number of advantages, including increased productivity, no human errors, and improved safety. Fully automated systems reduce the need for manual labor, which usually needs breaks, can be costly and prone to mistakes made by humans.

To achieve complete automation in the current scenario shown, the flow needs to be improved. There is manual portion of the flow which entails to inform the WMS about completed kitting processes by pressing a button on a tablet. This process involves human factor in the process and if done incorrectly, it could cause delays and errors. Apart from human error problem, involvement of humans in this activity disallow humans to concentrate on more value adding activities that are more beneficial for the operations of the company. Full automation, in most cases, leads to the reduction of the human workforce, which indeed, reduces cost from financial perspective. That is why, it is good to remove human factors from the system as much as possible and increase the automation levels. In the global level, there are different cases where AMRs communicate directly with the WMS without the need for manual input. Similar approach can be implemented in this factory setting so that once the kitting process completed, automatic order is received directly from production software to the MIR Fleet application. After this signal, robot starts to process the task.

Automation of order process

There are numerous software that dedicated to AMRs can be referred to as Transport Management Systems [34]. By using such software, companies can automate the order management process and remove human factors from the operation.

There are different ways of integration, such as via ERP and OPC UA Connector as shown in figure 26. In this research, the focus will be on integration with OPC UA Connector as this seems the recommended method for the current company setting.

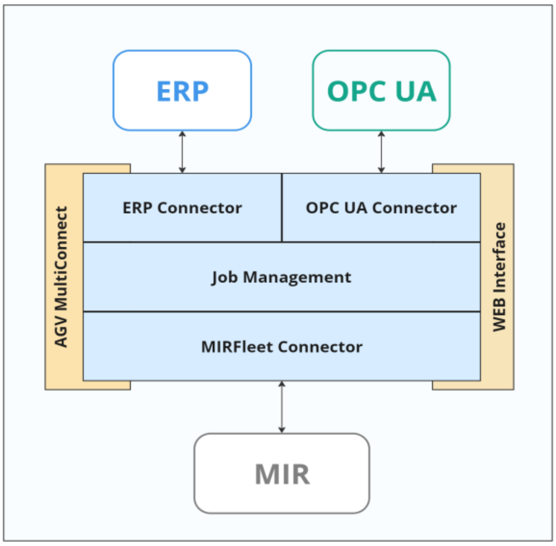

Figure 25. Integration via ERP and OPC UA

The OPC Foundation created the machine-to-machine communication protocol known as OPC Unified Architecture (OPC UA), which is used in industrial automation. The OPC UA platform utilizes an extensible framework with a platform-independent service-oriented architecture to integrate various OPC Classic specifications. OPC UA makes industrial connectivity easier so engineers can integrate all of the hardware, software, and automation systems using a safe and platform-independent standard.

It is possible to integrate order planning into the FLEET application with the help of OPC UA Connector. MiR transport robots will be started directly from different PLCs. While another PLC organizes transport orders to restock empty carriers for the production line, one PLC controls the transfer of carriers from the production line to a collection point. Without using an ERP system, the PLCs will be the only ones in charge of organizing all transportation. Middleware software is needed to connect OPC UA servers to the MiRFleet manager in order to achieve this. There is middleware available that can be installed and configured without the need for programming, called AGV MultiConnect [35]. By sending PLC variables to the middleware, the PLCs can launch a mission in the MiRFleet manager. The corresponding confirmation is sent to the PLC once the mission has been completed. Technicians can use the web-based diagnostic interface to locate the issue in the event of any malfunction. Integration of such technology will eliminate some (if not all) human factors from the system. General model is in figure 27.

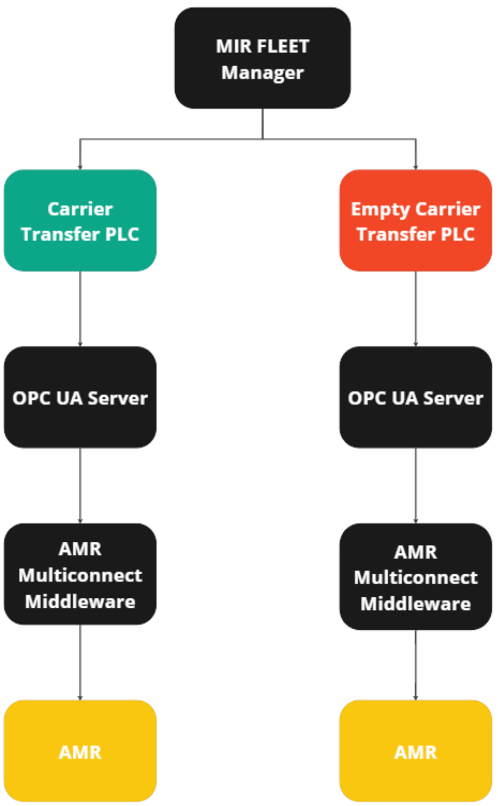

Figure 26. Integrated TMS with MiR transport robots

Integration of smart trolleys

The second area of technical improvements is related to trolleys. For the current factory, it will be beneficial to turn trolleys from being metal structures to smart entities. The main aim and benefit are to make trolleys part of the connected network. Since there are many different types of trolleys with different functions and capabilities in the production, being able to identify them automatically while operating will be a huge success in terms of waste reduction.

There are many different methods to make trolleys smarter. However, the author will focus on implementation through introduction of RFID tags and readers into the production layout. The RFID tags will be placed on each trolley entity and will be uniquely belong to it. As it was discussed in previous section, OPC UA and PLCs will be utilized to make sure of a smooth integration. Here are some general level steps of how OPC UA and PLC can be used to integrate smart trolleys:

- To detect the RFID tags on the smart trolleys as they move through the plant, RFID readers will be installed in key locations all around the path and key visit locations.

- Next, is to connect the RFID readers to a PLC so that it can collect data from the RFID tags. The RFID readers will be connected to a PLC.

- Using OPC UA, the PLC will be able to exchange data securely and consistently. This will enable real-time data to be sent from the smart trolleys to the plant's automation system.

- It will be beneficial to connect a custom web application software to guarantee that the information from the smart trolleys is accurately recorded in SAP, custom software needs to be created.

- The system will then be tested to make sure it is operating as intended before being installed in the plant.

Integrating trolleys to the server with the plant's automation system and enabling real-time data exchange will increase productivity. It will be possible to set up a logic system on the trolleys with the help certain sensors so that whenever a trolley stays idle in the production more than 65 minutes, the alarm system will inform the warehouse. Connection between trolley alarm system and AMR will result in improved AMR operating logic as it is in figure 28.

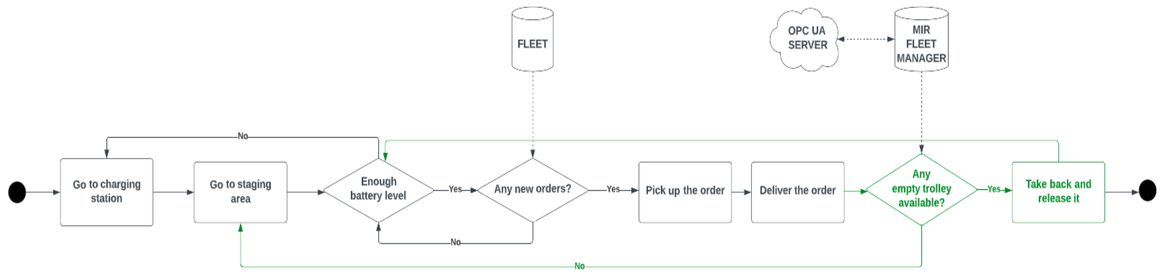

Figure 27. Improved AMR flow

Successful implementation of these systems will result in such benefits:

- It will be possible to know the quantity of components transferred from point A to B. It will create an easy and accessible tracking system indoors. Additionally, it will set up a new KPI (such as number of units transferred per operational AMR time) to track the status of material handling.
- Each trolley's location will be tracked by the system in real-time, improving planning and streamlining production processes.
- Each trolley's condition, such as whether it is full or empty, can be tracked and used to start an automatic replenishment or remove the trolley from the assembly line.
- To provide a complete picture of the production process and enable data-driven decision making, the data collected from the smart trolleys can be integrated with other systems.
- Sensors for monitoring temperature, humidity, and other environmental factors that might have an impact on the quality of the components being transported can be added to smart trolleys.
- Alarming system will not allow trolleys to stay in the production for a long time and increase the efficiency.
- Workers can concentrate on higher-value tasks, like maintenance or quality control, by reducing the need for manual tracking and monitoring of trolleys.

Overall, making trolleys intelligent can have a big impact on a manufacturing facility. It is possible to gain real-time visibility into production flows, cut waste, and optimize processes for greater effectiveness and productivity by integrating them into the smart network.

4.2.2 Layout and equipment standardization

The main focus of this chapter will be related to the pathways and trolley types standardization.

Trolley standardization

As it was mentioned before, there are more than 10 trolley types in the manufacturing layout. These trolleys have been custom made through years addressing to the different needs of different kinds of products. As new products were appearing, trolley types were also adjusted accordingly. In case of fundamental differences in the shapes of components, new trolleys were introduced. AMRs have been introduced only recently to the company. Around 50% of all trolley types have been adjusted based on the AMR needs. This has significantly affected the operations of the AMRs, as up until now, AMR work has been adjusted based on the trolley types they are. Not fully AMR-compatible trolley types result in limited types of components to be transported by AMRs. Limited capability of transportation results in under-utilization of all routes. Therefore, it is important for the company to invest in reworking of all trolley types and increase the ratio of AMR-compatible trolleys. Another aim should be related to decreasing the total types of trolleys. This will result in more simplified processes in finding the correct trolley type for kitting process and so on.

Figure 28. Custom cart design for AMR MIR250 [36]

There are different companies around the world that deal with designing and developing trolley and cart solutions for the organizations with AMR on layout. One of the very important steps of trolley design is to make sure that the dimensions and structure of the design do not hinder the sensors and cameras installed on AMRs as in figure 30. Otherwise, AMRs will not function as intended.

It is proposed by the author to rework trolleys based on the routes. As an example, in case if there are total of seven delivery points, total types of trolley should also match the number. In case there are new types of products introduced, part of the trolleys can be reworked again in a short time.

Pathways standardization

For any company that wants to introduce AMRs into the manufacturing layout, there are few important parts need to be considered. The pathways in the production area should be arranged so that AMR together with the carriage can easily navigate in the pathway. Width of the pathway should allow effortless navigation of AMRs and the trolleys. Of course, there is no specific width number as it is certainly dependent on the dimensions of the trolley or cart AMR transports. Moreover, areas with incline or decline are potential problems for AMRs. This is especially an issue if the components are very fragile and prone to damage with some vibrations. MIR100 robots are operational up to 5% decline/incline level.

When incorporating AMRs into a factory layout, the number of corners on the pathway is certainly an important issue to consider. Sharp turns slow down AMR navigation and increase the likelihood of collisions with other objects. AMRs navigate the manufacturing area using a variety of sensors and cameras; however, these sensors have limits around sharp corners. The sensors may not be able to identify obstacles around a corner if the pathway has too many steep turns, which could cause collisions or delays.

Lastly, it is important to keep the pathways out of slippery liquids and any dynamic obstacles, such as operator seats, idle trolleys, boxes and so on. Even though AMRs can detect and avoid such problems, any unforeseen obstacle on the pathway causes delays in the operations. Manual transportation can easily avoid these problems, but in AMR case, keeping the path clean is a key to success.

4.2.3 Introduction of New Routes

Referring back to figure 19, it could be seen that the utilization level of routes in the factory layout is around half level. Currently, there are only 4 delivery points in 4 different production lines. These deliveries are completed using only 4 partly overlapping routes (shown in black). However, there are multiple more delivery points that have components transported in a manual way. Overall, the number of combination of those routes are quite higher than current AMR-compatible routes. The primary reasons behind not utilizing AMRs for those deliveries are related to non-compatible trolley types, narrow pathways, uneven surfaces, and so on. In this chapter, the author will assume the incapabilities of the equipment and layout. Author will discuss the potential additions on the routes and establish different scenarios to be simulated in Visual Components software.

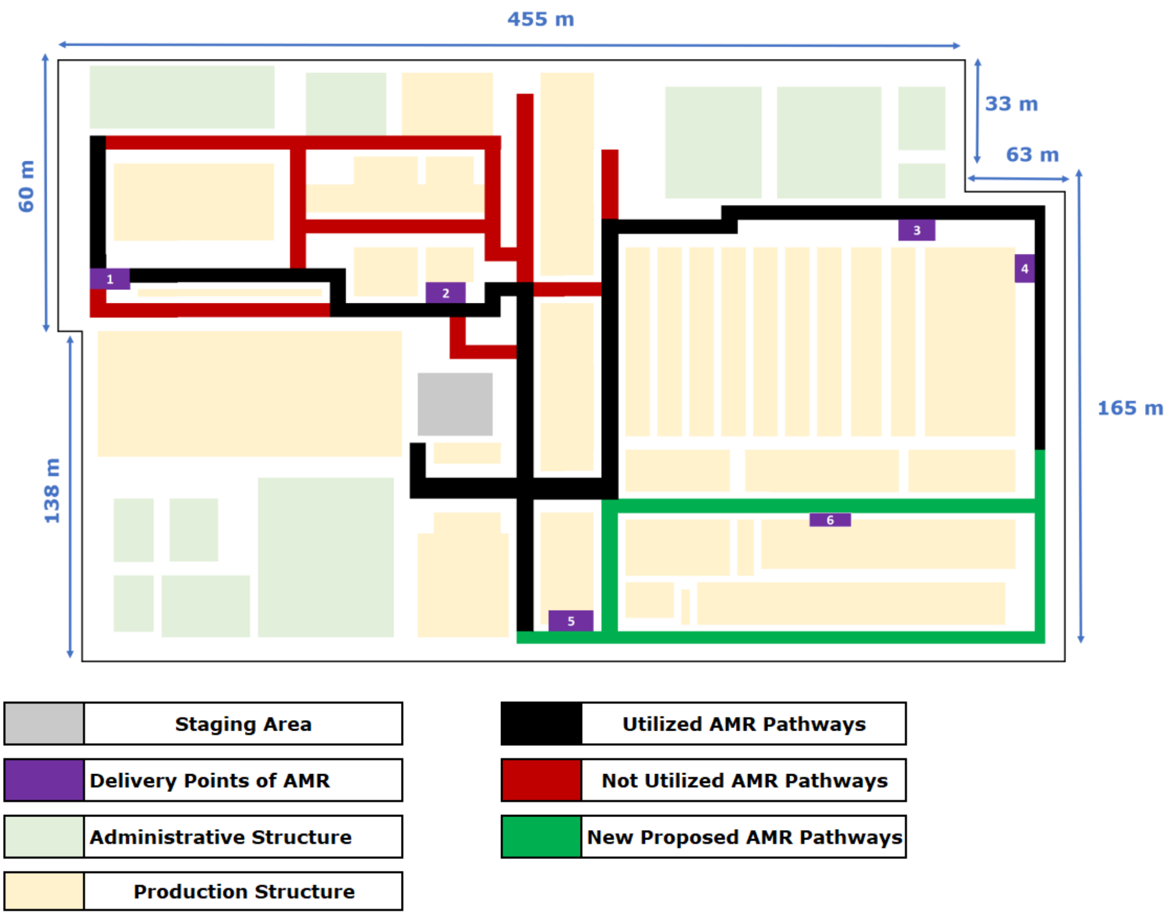

Figure 29. Layout with proposed changes

According to the overall activity of the production plant in the recent years, author proposed to add AMRs into three more delivery points in the production layout visualized in figure 30. The newly added routes have been shown in green color. Delivery point 6 is related to sub-structure production for all the final assembly units in the company just. Therefore, these points are highly busy and require in time delivery. Instead of transporting raw components for the initial production, for the point 5, AMRs will be used to transport the final products to the warehouse after the final testing. The key mention here is that specifically designed trolleys can only carry one product at a time. As an example, in case if there will be 50 pieces shiftly demand, the AMR should travel the same route 50 times. Mathematical modeling will provide optimal split of robots for this activity in the next chapter.

Overall, there will be 2 different scenarios to be simulated with different settings.

Table 8. Simulation scenarios

Scenarios	Simulation Setting
1	All available and proposed routes with current demand level and with current energy management principle on one-way paths – only charging when robot battery lowers to 60%.
2	All available and proposed routes with higher demand level and with continuous charging energy management principle on two-way paths – two-way movement in all pathways.

4.3 Scenario simulations with different improvements

In this chapter, proposed changes in the routes will be simulated with the help of Visual Components software. Multiple simulations will be modeled based on the demand availability levels and with three recently added delivery points. Mathematical modeling will be used in order to allocate the efficient number of robots into each route. Once the output from mathematical model is collected, robots will be allocated to the routes accordingly. Simulations will be made in order to simulate 12 hours of production time.

Based on the improvements noted in the previous chapters related to trolleys and routes, it should be noted that delivery point 1 and 6 will be on the same trolley type as the components transported are quite similar.

Table 9. Trolley adjustments

Route	Current AMR Trolley Type	Proposed AMR Trolley Type
Delivery Point 1	Built-in trolley on AMR	Built-in trolley on AMR
Delivery Point 2	Type D, A, F	Type D, A, F
Delivery Point 3	Type E	Type E
Delivery Point 4	**Type C, G**	**Type C**
Transport Point 5	**None**	**Type X**
Delivery Point 6	Built-in trolley on AMR	Built-in trolley on AMR

Simulation models will be performed based on the above adjustements. The results will be compared with the initial simulation using key performance indicators. The best scenario among the simulated ones will be selected for implementation. At the end of the chapter, cost analysis and the human resource analysis will be performed based on the selected scenario.

4.3.1 Scenario #1: Addition of new routes with current demand level using one-way transportation and existing energy management

As it can be recalled from current factory simulation, current demand levels and need for trolleys have been calculated. Here is the current demand look based on the new trolleys adjustments.

Table 10. Updated trolley view after initial changes

Trolleys	Total Need Weekly (in units)	Total Need Shiftly (in units)	AMR Compatible
TYPE A	181	19	yes
TYPE C	229	21	yes
TYPE D	30	3	yes
TYPE F	35	3	yes
TYPE I	184	14	no
TYPE H	33	4	no
TYPE E	107	10	yes
TYPE X	184[3]	14	yes

Table 11. Trolley need per route

Routes	Trolley Type	Trolley need per shift (in units)
Delivery Point 1	Built-in Trolley on AMR	25
Delivery Point 2	D, A, F	25
Delivery Point 3	E	10
Delivery Point 4	C	19
Transportation Point 5	X	14
Delivery Point 6	Built-in Trolley on AMR	31

The output of the mathematical model provided a feasible robot allocation for each route as shown in figure 32. Code is visible in Appendix 5.

```
----     71 VARIABLE x.L  if AMR i is assigned to route j

            j1          j2          j3          j4          j5          j6

i1                                                                   1.000
i2       1.000
i3                                 1.000
i4                                             1.000
i5                                                         1.000
i6                                                         1.000
i7                   1.000
```

Figure 30. Model output for AMR allocation

[3] Same as weekly demand since for this specific node, there could be only one component fitting onto each trolley.

According to the above table, the assignment of robots to delivery points are as follows:

Table 12. Robot assignment to routes

AMR 1	Delivery Point 6
AMR 2	Delivery Point 1
AMR 3	Delivery Point 3
AMR 4	Delivery Point 4
AMR 5	Transportation Point 5
AMR 6	Transportation Point 5
AMR 7	Delivery Point 2

Table 13. Simulation #1 settings

Simulation Scenario #1 Settings	
Energy Management	Charging up to 90% once battery level drops to 60%
Pathways	70% of pathways one-way, 30% two-way
Demands Level	Low
Time	12 hours
Layout	Proposed layout model
AMR	Proposed allocation

After the simulation for the proposed changes, results have been collected and statistics are as in figure 32.

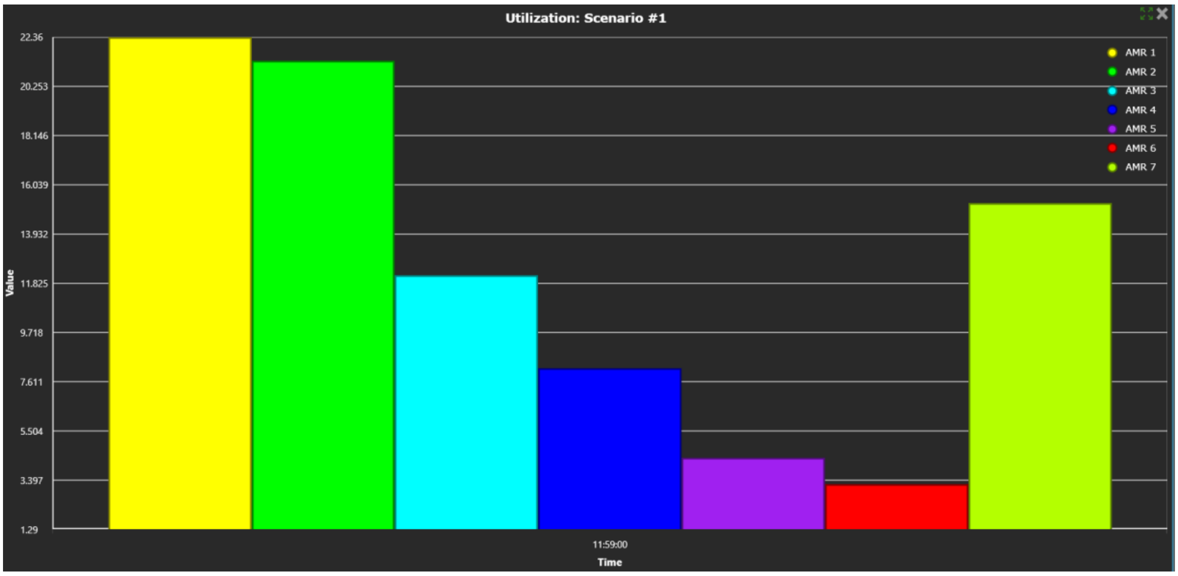

Figure 31. Scenario 1 - utilization Rates - bar chart view

Other statistics can be found in Appendix 6. With the improvements made, there is apparent improvement in values.

Table 14. Realized change in simulation in the proposed system

AMR	Utilization with Existing System (in %)	Utilization with Scenario 1 (in %)	Realized Change (in %)
1	9.62	22.35	**12.73**
2	3.13	21.34	**18.21**
3	5.32	12.18	**6.86**
4	6.91	8.2	**1.29**
5	6.5	4.34	**-2.16**
6	8.59	3.21	**-5.38**
7	10.04	15.27	**5.23**
Average Change			**5.25**

It is quite natural tendency to have negative changes when there are some significantly incomparable positive changes. AMR 5 and 6 have been allocated for the Transportation Point 5. In that node, we had demand of only 14 products per shift. This indeed caused some underutilization with the robots since mathematical model has allocated these robots based on significantly high demand.

Moreover, in the last simulation, there is a noticeable problem arised.Cheking the figure 33, it should be noted that in four of the six delivery nodes, we have some delays as shown with red oval shaped windows. Delay in production is not tolerated as it causes significant problems and reduces the efficiency. This is especially the case when demand is quite high and every single delay causes disruptions and late deliveries.

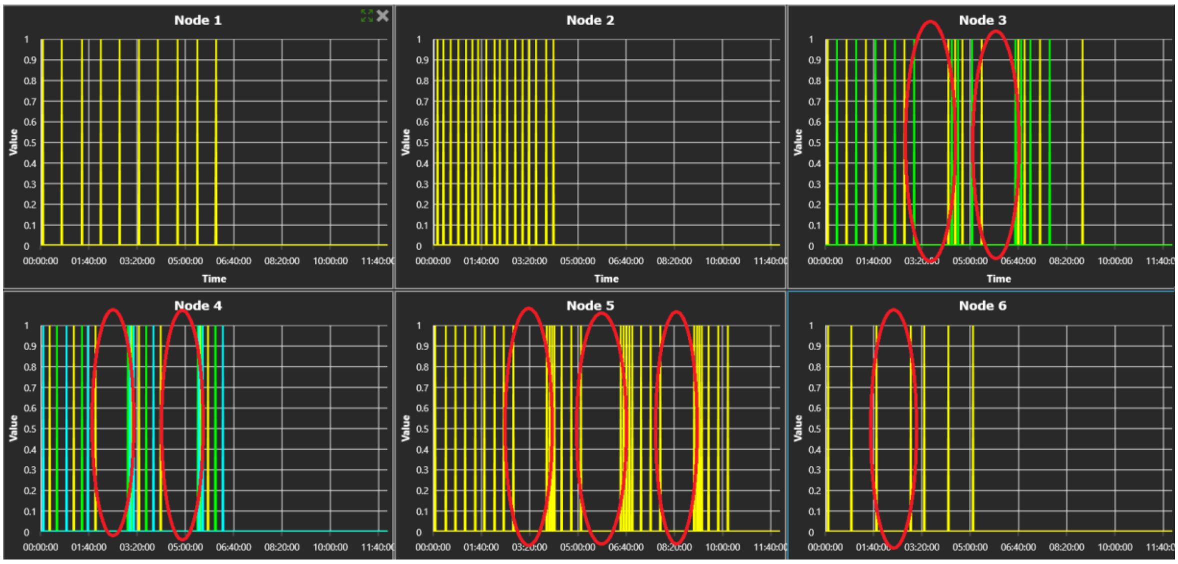

Figure 32. Delivery intervals to six nodes with delays shown

The main reason behind the delays is the battery levels of robots. In the continuous operations and with low level of maintenance, robots consume significantly more energy and once it hits certain threshold, which is 60% in the simualtion, robots need to be charged up to 90% in order to continue normal operations. As it was discussed in previous chapters, there are some research studies that focus on setting locations for charging points and find the best charging limits for the robots using different methods and models [13, 21]. However, this is not the main focus of this research study. However, in order to avoid such problems real cases, most of the organizations rely on principle of always charging the robot when it is idle. Additionally, setting the correct threshold levels is also important. Therefore, it is decided to reduce the difference gap between required minimum and charging maximum battery levels. For example, if the robot needs to charge up to 90% when battery lowers to 60%, then it will require more time to reach that level. Instead it would good idea to have 80% and 65% charging levels, respectively.

4.3.2 Scenario #2: Addition of new routes with higher demand level using two-way transportation and continuous charging energy management

In this scenario, without exceeding realistic levels and taking the past demands into account, demands are increased to a certain. Here are the updated demands.

Table 15. New demand levels

Product	Weekly Plan (in units)
PRODUCT 1 V1	840
PRODUCT 2 V1	756
PRODUCT 2 V2	453
PRODUCT 1 V2	456
PRODUCT 2 V3	300
PRODUCT 3 V1	876
PRODUCT 3 V2	564
PRODUCT 2 V4	120

Using the calculation model, table below has been populated.

Table 16. Trolley need based on higher demand

Trolleys	Total Need Weekly (in units)	Total Need Shiftly (in units)	AMR Compatible
TYPE A	350	25	yes
TYPE C	364	26	yes
TYPE D	70	5	yes
TYPE F	70	5	yes
TYPE I	1456	104	no
TYPE H	294	21	no
TYPE E	210	15	yes
TYPE X	1456[4]	104	yes

Here are the settings for the 2nd simulation model:

Table 17. Simulation scenario #2 settings

Simulation Scenario #2 Settings	
Energy Management	Always charging unless robot is busy
Pathways	All pathways two-way
Demands Level	High
Time	12 hours
Layout	Proposed layout model
AMR	Proposed allocation

Based on the seasonal increased demands, simulation scenario has been created and simulation has been completed. It should be noted that Below, are the output from the second simulation scenario.

Table 18. Current state and Scenario 2 comparison

AMR	Utilization with Existing System (in %)	Utilization with Scenario #2 (in %)	Realized Change (in %)
1	9.62	35.68	**26.06**
2	3.13	32.24	**29.11**
3	5.32	29.59	**24.27**
4	6.91	6.64	**-0.27**
5	6.5	9.57	**3.07**
6	8.59	35.14	**26.55**
7	10.04	26.06	**16.02**
Average change			**17.83**

[4] Same as weekly demand since for this specific node, there could be only one final product fitting onto each trolley.

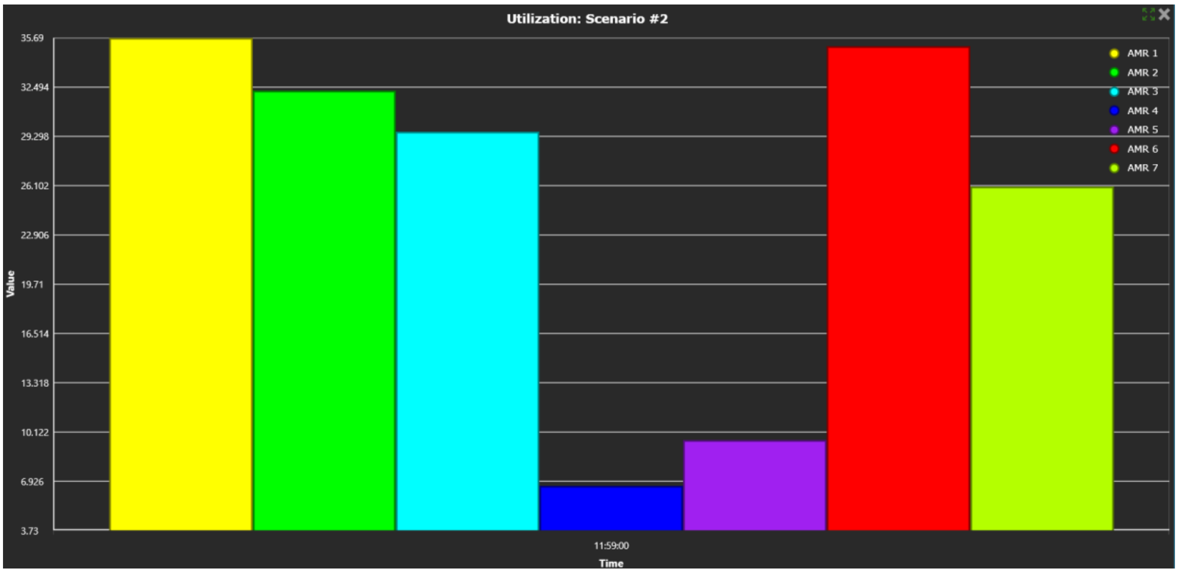

Figure 33. Scenario #2 - utilization levels of amrs - bar view

According to figure 34, results from the Scenario #2 was overall higher than the Scenario #1 as it was expected. According to the simulation data and output, 7 robots have been enough to handle high demand with the proposed changes. Other statistics can be found in Appendix 6. Also, video from scenario 3 can be found under Appendix 8.

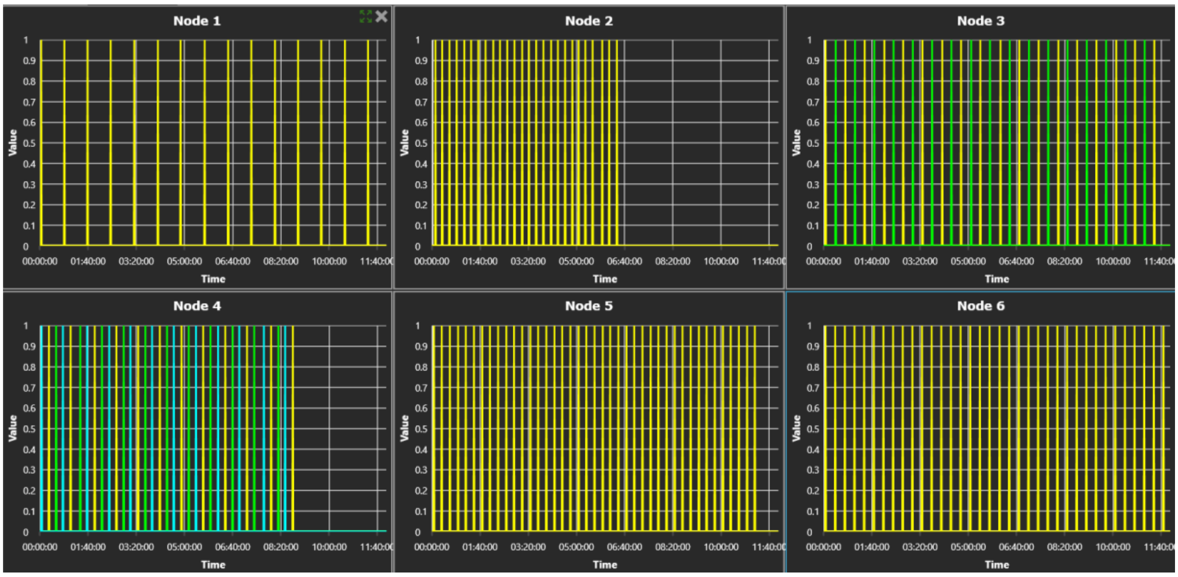

Figure 34. Scenario #2 - delivery intervals

Considering the Figure 35 visualization, it can be concluded that there were no more delays based on the delivery intervals due to the better battery management system. This proves the robustness of the oprations in the system.

However, it is also seen from the graps that there have been high frequency deliveries almost until the end of the whole period (12 hours) in 3 different routes. This means that in case of significantly higher demand, 7 robots might not be enough. In order to maintain the robustness of the intralogistics for even higher demand rates, addition of few robots might be even more beneficial.

4.4 Cost analysis

In this section, brief cost analysis will be performed. It should be noted that all salary figures are not related to the existing company data and are purely based on average salary levels of similar professions on Statistics Estonia portal [37]. There are currently 8 workers that allocated their 60% time into the trolley transportations and 40% of time for loading and unloading materials, breaks, and other warehouse related tasks. In addition to this, according to the simulation data, average time between transportation order initiation and delivery of trolleys for each delivery point are shown in table 19.

Table 19. Average transportation cycle time for each robot based on simulation

AMR	Delivery Location	Average Time Needed for 1 transport (in minutes)[5]
AMR 1	Delivery Point 6	6.3
AMR 2	Delivery Point 1	7.16
AMR 3	Delivery Point 3	4.1
AMR 4	Delivery Point 4	9.2
AMR 5	Transportation Point 5	6.3
AMR 6	Transportation Point 5	6.3
AMR 7	Delivery Point 2	6.1

Considering the third scenario where there was high demand for all product segments, total needed time to deliver all components would be as follows.

Table 20. Total AMR transportation time based on scenario #3

AMR	Total Transports per Shift	Total Time Needed (in minutes)
AMR 1	41	258.3
AMR 2	35	250.6
AMR 3	15	61.5
AMR 4	26	239.2
AMR 5	60	378
AMR 6	44	277.2
AMR 7	35	213.5
	Total	**1678.3**

[5] Numbers are based on simulation results

In the analysis of the cost and human resource allocation, the research will consider 12 hours shift periods as an average company setting. In case there are 8 workers allocating 60% of their operational time for component transportations, total number of time available from the perspective of one worker are as follows:

Table 21. Worker's time allocation for transportations for 12 hours shift setting

Total Working Time	720 minutes
Breaks (food, needs, distractions) (10%)	72 minutes
Operational Time	648 minutes
Operational Time for Transportations (60%)	388.8 minutes

If there are 8 workers, then total operational time available for transports is 3110,4 minutes if there were no AMRs available. In table 20, it was concluded that after fully implementing AMRs, they will perform 1678,3 minutes of work, which is about 54% of the maximum available workload capacity. In other words, it is possible to remove 1678,3 minutes of manual work from the system.

$$\frac{1678{,}3\,minutes}{388{,}8\,minutes} = 4.32\,workers$$

In conclusion, it possible to reduce 4 workers from the existing system. Partial remaining workload will be allocated for other tasks to reduce overload from the rest of the workers. Salary level for each of the transportation worker is around around 1574 EUR[6]. It should be noted that the salary information for each worker in this chapter is taken as the average salaries of similar roles in Estonia, provided by Statistics Estonis website [37].

In the implementation phase, there will be many technical tasks to be performed by engineers, such as establishing technical ecosystem and connecting the updates with the existing system. Successful implementation depends on the project team, skill sets, and time according to a robotics blog [38]. Here are the recommended job roles in the project:

Project Manager – to ensure project objectives are met in the given timeline and budget restraints. Average salary level: 3771 EUR

[6] The salary numbers provided in this chapter are purely based on the Statistics Estonia portal [37] and does not represent actual company salary numbers.

Robotics Engineer – to desing, develop, and test the software and hardware components of the AMRs. Average salary level: 2120 EUR

Software Developer – to develop and maintain the interface for integration of AMRs with the production system and esure that the system is robust. Average salary level: 4188 EUR

Industrial Engineer – to analyze the existing flow, identify areas for improvements, and to develop strategies to optimize the system. Average salary level: 2554 EUR

Table 22. Monthly project cost

Job Role	**Monthly Salary**[7]
Project Manager	3771 EUR
Robotics Engineer	2120 EUR
Software Developer	4188 EUR
Industrial Engineer	2554 EUR
Total Monthly Project Team Cost	**12633 EUR**

Overall estimated timeline is estimated around 8 months considering possible delays, testing, maintenance, trainings.

It is recommended not to reduce the existing transportation workforce unless there are significant improvements with AMR utilizations, routes, and applications. Possible reductions can be made after the implementations phase once the certain AMR utilization levels would be achieved and certain part of all transportation tasks have been fully replaced by AMRs. According to the simulation view, AMRs can perform around 54% of the all transportation tasks when the demand are high. In case of even higher demand numbers, there will be a need for new AMRs and also for new workers.

Project team will be implementing the solutions for 8 months. Until that time transportation workers will stay in the company and only after 8 months, manual working hours equivalent to around 4 people will be reduced. Considering investments related to trolleys, software ecosystem, maintenance, and the total duration of the project, estimated time for cost breakeven will be in around 47 months. Since there is no additional investment apart from project team cost, changes of cost in overhead, energy, and equipment are negligible and negligible. Details can be seen in Appendix 7.

[7] The salary numbers provided in this chapter are purely based on the Statistics Estonia portal [37] and does not represent actual company salary numbers.

5. DISCUSSION

In this research project, with the help of multiple scientific methods, certain optimization and improvements have been achieved in the simulation settings. Implementation should be completed in order to realize the practical optimization in the real production intralogistics setting. Research questions have been discussed in detailed and numerical ways throughout the thesis. Below are the summarized findings to the main questions.

1) What are the requirements and challenges of material transportation in production intralogistics?

Material handling is consisted of highly complex flow of materials, workers, vehicles in the system. Good material handling flow should be performing based on clearly stated guidelines, predetermined way of work, and most importantly, without delays. As it was highlighted in details in the paper, operational and environmental factors have significant influence on the state of material handling. Applied material handling systems often face certain problems, such as non-standardized equipment and layout. This paper highlighed certain problems in the example company setting and proposed solutions to avoid those cases. Optimized utilization of decentralized entities, such as AMRs, are proposed to be the best actor for dynamic environments.

2) How to organize, plan and control AMRs for material transportation in intralogistics for better utilization?

Technological advancements made in AMR field allow these robots to be the best actors when it comes on planning and control of intralogistics. When combined with ERP systems, it is possible to establish configurations that do not require any human factor to be available for transportation operations. Apart from that, usage of methodologies such as mathematical modeling and simulation modeling allow to foresee possible problems beforehand at no cost and allows the users to take action before even implementing real settings for AMRs in the layout.

3) How to organize robust AMR setting against seasonal demand changes?

Once the good utilization levels achieved with multiple optimization activities, seasonal changes can only be subject to the number of AMRs. With consistent high levels of utilization, it is possible to fully understand and utilize the capacity of the robots. This way, decentralized entities such as AMRs can be viewed as capacity objects. Having this information available, it is possible to be ready for the upcoming demand cycles. In case of significantly higher demands, addition of AMRs can be considered.

SUMMARY

The main aim of this thesis was to analyse the existing production intralogistics with deeper focus on AMR utilization rates. Research has been performed using the available information and data from one of the manufacturing sites in Estonia.

Problems related to current state material handling and AMR processes have been identified and improvement ideas have been proposed. This research serves as a framework as how production intralogistics should be optimized and what factors and performance measure should be considered in the existence of AMRs. Moreover, optimizations have been based on strong essence with use of scientific tools, such as mathematical modelling and simulation modelling. Current state and proposed state have been simulated in total of 3 scenarios and the achieved increase of overall utilization have been 17.8% with higher demand levels and 5.25% with current demand levels.

Possible implementation timeline has been proposed based on realistic inputs. Project need to be implemented for 8 months and ROI will be realized in 47 months. Optimized AMR flow would allow material handling to significantly reduce excessive waste and to be more organized and robust to disruptions. Based on optimized intralogistics, AMR utilization rates improved and delays on component delivery have been significantly minimized. Additionally, proposed improvement ideas will help to reduce 50% of headcount associated with intralogistics. Results of the research project will be reviewed and analysed while performing the implementation in the actual and practical setting.

Production facility planners need novel methods to increase flexibility, productivity, quality and at the same time to reduce costs and face challenges. Improving intralogistics in manufacturing has a lot of possibilities. AMRs might be one of the answers that manufacturers need to continually support the development of intralogistics. The goal of implementing AMRs in industrial intralogistics is to move away from manual material transportation toward automated and ultimately autonomous material transportation. Decentralized control backed by AI can be very useful in preserving intralogistics at a high level and allowing industrial workers to concentrate on core tasks.

Overall, this thesis provides comprehensive framework for the optimization of intralogistics in AMR implemented environments.

KOKKUVÕTE

Käesoleva lõputöö eesmärk oli analüüsida tootmise logistikat, keskendudes AMR-i kasutuse mahtudele. Uurimuse läbiviimisel on kasutatud olemasolevat teavet ja andmeid ühest Eesti ettevõttest.

Tuvastatud on praeguse seisukorra materjalikäsitluse ja AMR protsessidega seotud probleemid ning pakutud välja parendusettepanekuid. Uurimus pakub ettepanekuid tootmise sisemise logistikat optimeerimiseks ning pakub milliseid tegureid ja toimivusmeetmeid tuleks AMR-ide olemasolul arvesse võtta. Optimiseerimise ettepanekute aluseks on matemaatiline modelleerimine ja simulatsioonimodelleerimine. Hetkeseisu ja pakutud olekut on simuleeritud kokku 3 stsenaariumis ning saavutatud üldise kasutuse kasv on kõrgema nõudluse tasemega olnud 17,8% ja praeguse nõudluse tasemega 5,25%.

Töös on realistlike sisendite põhjal välja pakutud võimalik rakendamise ajakava Projekti oleks vaja ellu viia 8 kuud ja ROI realiseerub 47 kuuga. Optimeeritud AMR-voog võimaldaks materjalide käitlemisel märkimisväärselt vähendada liigset jäätmeid ning olla organiseeritum ja häirete suhtes vastupidavam. Optimeeritud intralogistika põhjal on AMR-i kasutusmäär paranenud ja komponentide tarnimise viivitused on oluliselt viidud miinimumini. Lisaks aitavad pakutud parendusideed vähendada 50% intralogistikaga seotud töötajate arvu. Uurimisprojekti tulemused vaadatakse läbi ja analüüsitakse rakendamise käigus tegelikus ja praktilises keskkonnas.

Tootmisrajatiste planeerijad vajavad uudseid meetodeid, et suurendada paindlikkust, tootlikkust, kvaliteeti ning samal ajal vähendada kulusid ja tulla toime väljakutsetega. Tootmise siselogistika täiustamisel on palju võimalusi. AMR-id võivad olla üks vastustest, mida tootjad peavad intralogistika arendamisel pidevalt toetama. AMR-ide rakendamise eesmärk tööstuslikus siselogistikas on liikuda käsitsi materjalide transpordilt automatiseeritud ja lõpuks autonoomse materjalitranspordi suunas. AI-ga toetatud detsentraliseeritud juhtimine võib olla väga kasulik intralogistika kõrgel tasemel säilitamisel ja võimaldab tööstustöötajatel keskenduda põhiülesannetele.

Kokkuvõttes annab käesolev lõputöö raamistiku intralogistika optimeerimiseks AMR-iga rakendatud keskkondades.

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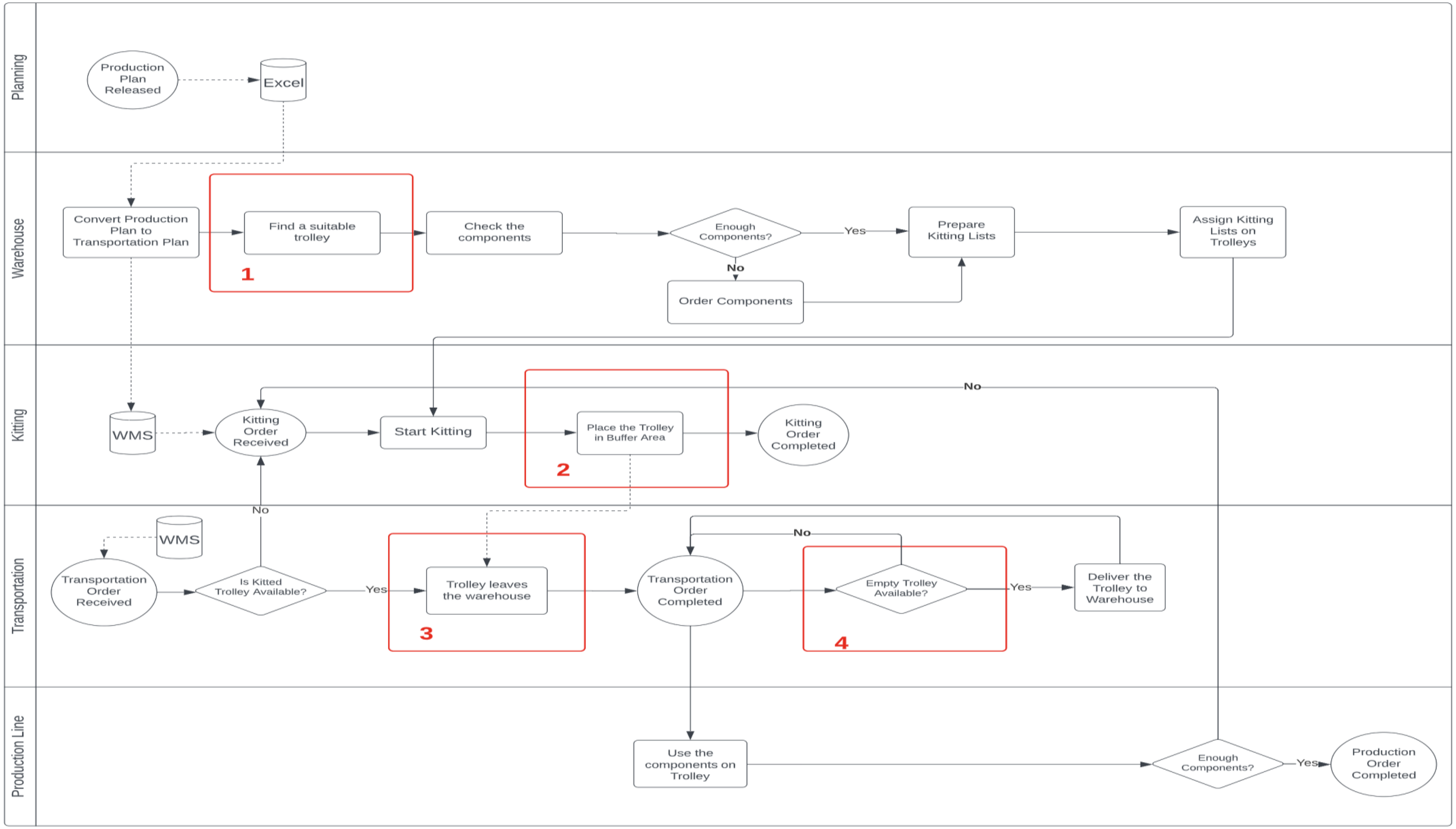
APPENDICES

Appendix 1. Material handling procedure

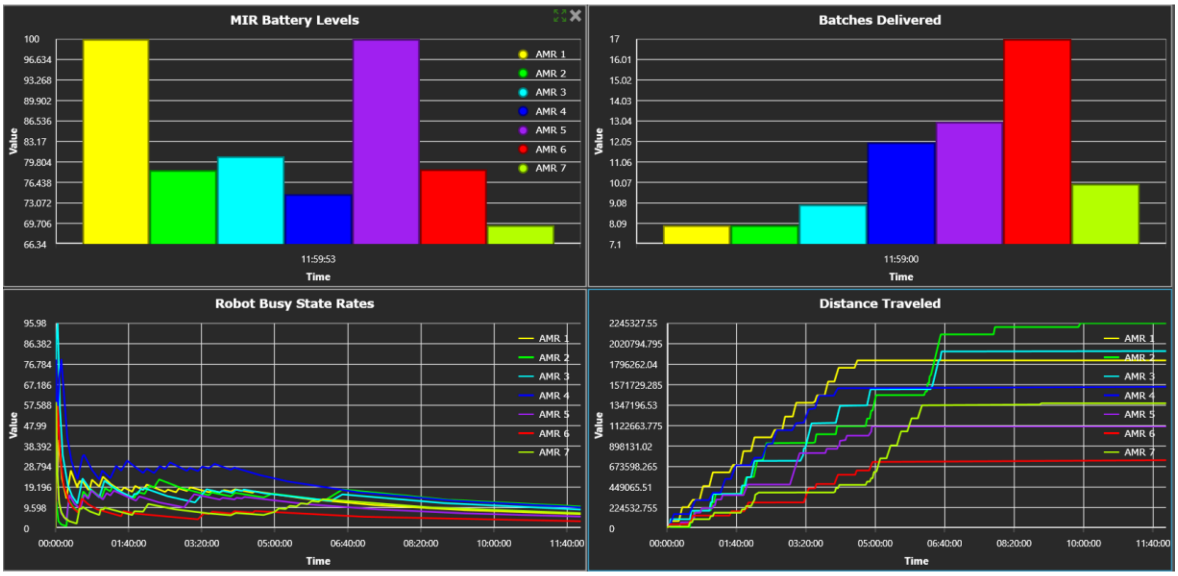


Appendix 2. MIR100 technical specifications

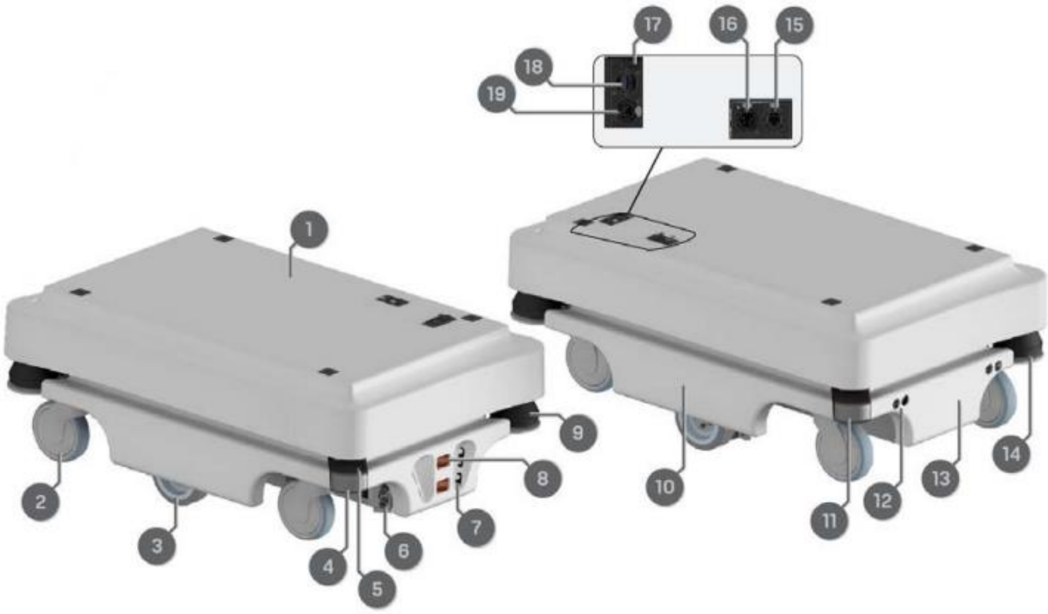
General Information	
Designated use	Autonomous mobile robot (AMR) for internal transportation of smaller loads
Color	ABS 542D / ATHLONE White (RAL9003)
Disclaimer	Specifications may vary based on local conditions and application setup
Dimensions	
Length	890 mm | 35 in
Width	580 mm | 22.8 in
Height	352 mm | 13.9 in
Ground clearance	50 mm | 2 in
Weight	77 kg | 170 lbs
Payload	
Maximum payload	100 kg | 220 lbs (maximum 5% incline)
Speed and performance	
Maximum speed	1.5 m/s (5.4 km/h) | 4.9 ft/s (3.6 mph)
Operational corridor width	With default setup: 1 000 mm | 39.4 in
Positioning accuracy (in controlled conditions)	Docking to VL-marker: ± 11 mm | 0.43 in on X-axis, ± 9 mm | 0.35 in on Y-axis, ± 1° yaw, Moving to position: ± 26 mm | 1.02 in on X-axis, ± 8 mm | 0.31 in on Y-axis, ± 3° yaw
Traversable gap tolerance	Up to 20 mm | 0.79 in
Active operation time with maximum payload	Up to 7 h 30 min (24V Standard battery)
Active operation time with no payload	Up to 9 h (24V Standard battery), up to 13 h (24V Extended Capacity battery)
Standby time (robot is on and idle)	8 h 51 min (24V Standard battery), 23 h (24V Extended Capacity battery)
Maximum incline/decline	± 5% at 0.5 m/s
Power	
Battery type	Lithium-ion, 24V, 33.6 or 56 Ah
Charging ratio	Up to 1:6 charging to runtime ratio

Charging current	Up to 25 A
Number of full charging cycles	Minimum 1 000 cycles
Environment	
Environment	For indoor use only
Ambient temperature range, operation	5–40°C | 41–104°F
Humidity	10–95% non-condensing
IP rating	IP 20
Floor conditions	No water, no oil, no dirt
Compliance	
EMC	EN61000-6-2 and EN61000-6-4
Cleanroom	Class 4 (ISO 14644-1)
Safety standards for industrial vehicles	CE, EN1525, ANSI B56.5, RIA15.08
Communication	
WiFi	2.4 GHz 802.11 g/n, 5 GHz 802.11 a/n/ac.
I/O connections	USB and Ethernet
Sensors	
SICK safety laser scanners	2 pcs, S300 (front and rear), give 360° visual protection around the robot
3D cameras	2 pcs, 3D camera Intel RealSense™ D435 | 2–70.9 in
Lights and audio	
Signal and status lights	Indicator lights on four sides

Appendix 3. Current state simulation statistics



Appendix 4. MIR100 external parts



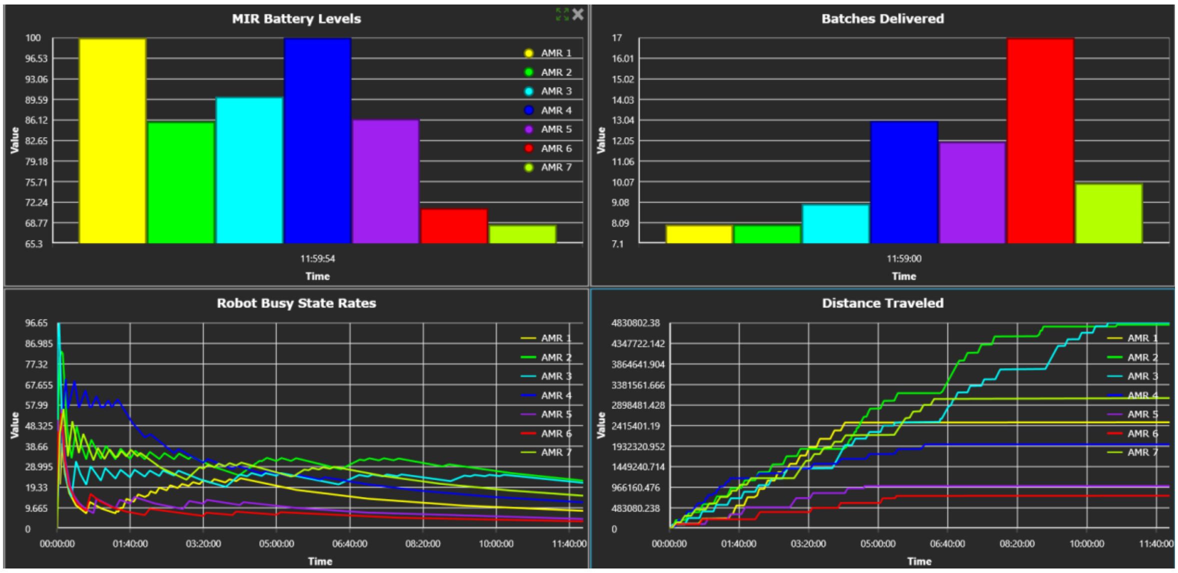
Position	Description
1	Top cover: access to internal parts
2	Swivel wheel: four pcs., one in each corner
3	Drive wheel: two pcs., differential control
4	Behind the removable corner cover: HDMI port and USB service port - connects to the robot computer
5	Scanner reset button (yellow) and On/Off button (blue)
6	Ultrasound sensors: two pcs., for detection of transparent objects (side)
7	3D depth camera: two pcs., both in the front
8	Pad connectors: two pcs., for connection to charging pins on MiR Charge 24V charging station
9	S300 safety laser scanner (front)
10	Side cover
11	Behind removable rear corner cover: Charging port with switch
12	Ultrasound sensors: two pcs., for detection of transparent objects (rear)
13	Rear cover
14	S300 safety laser scanner (rear)
15	RJ45 Ethernet
16	Application power: for connection to top modules such as hooks
17	Antenna socket
18	USB interface - connects to the robot's PC
19	Emergency stop interface: with added options for connection to small units and I5 input on SICK scanners

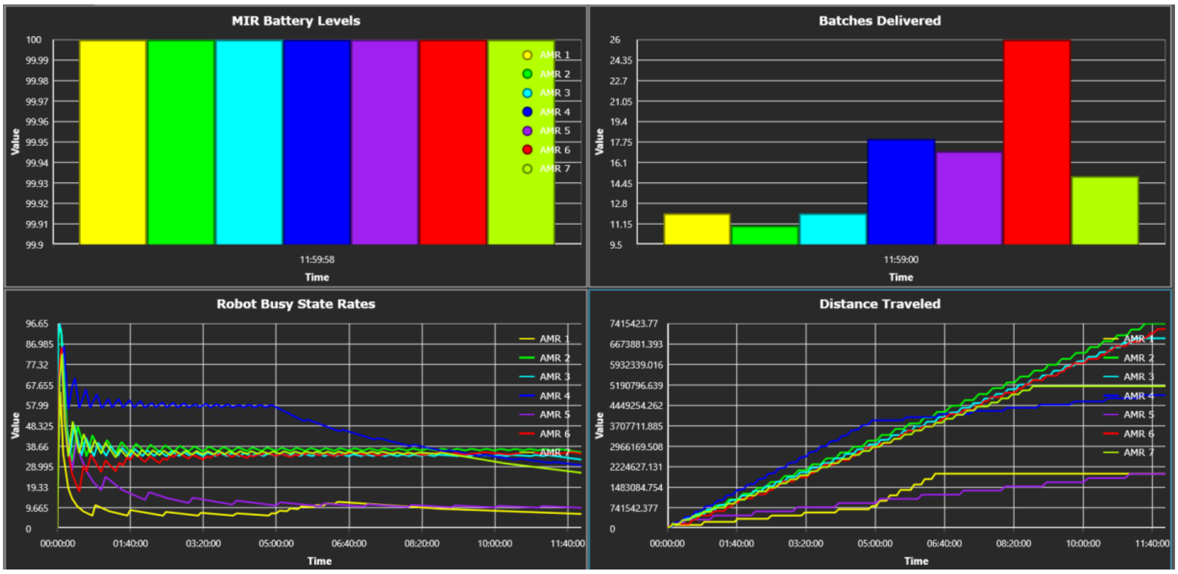
Appendix 5. Mathematical model code

```
$title AMR Routing Problem


$onText
This model has been developed to provide simple and straightforward method
of
optimizing the allocation of AMRs into different routes considering
constraints such as time, battery, robot capacity, and route demands.

Author: Turan Azizov
Institution: Tallinn University of Technology
Purpose: Master's Thesis

Keywords: mixed-integer modeling, intralogistics, AMR, optimizaiton, routing
$offText

Set
    i AMRs / i1,i2,i3,i4,i5,i6,i7 /
   j routes / j1,j2,j3,j4, j5, j6 /;

Table u(i,j) 'utilization of AMR i in route j'
                  j1     j2     j3     j4    j5    j6
    i1            0.8    0.1    0.1    0.1   0.1   0.9
    i2            0.8    0.1    0.1    0.1   0.1   0.9
    i3            0.1    0.1    0.9    0.8   0.1   0.1
    i4            0.1    0.1    0.9    0.9   0.1   0.1
    i5            0.1    0.9    0.1    0.2   0.9   0.1
    i6            0.1    0.9    0.1    0.2   0.9   0.1
    i7            0.1    0.9    0.1    0.2   0.9   0.1 ;

Table t(i,j) 'battery usage for AMR i in Route j'
                   j1     j2    j3    j4    j5    j6
     i1           0.05   0.03 0.05 0.06 0.02 0.03
     i2           0.05   0.02 0.05 0.06 0.02 0.03
     i3           0.04   0.02 0.04 0.01 0.02 0.03
     i4           0.04   0.02 0.03 0.01 0.02 0.02
     i5           0.06   0.02 0.04 0.01 0.02 0.04
     i6           0.06   0.02 0.04 0.01 0.02 0.03
     i7           0.06   0.02 0.05 0.01 0.02 0.03     ;

Parameter
    c(i) 'capacity AMR' / i1 250, i2 250,i3 300,i4 300,i5 270,i6 270,i7 270/
   b(i) 'min battery level of AMR' /i1 0.6, i2 0.5, i3 0.6, i4 0.6, i5 0.6,
i6 0.6, i7 0.6/
   r(j)  'demand route'    / j1 100,j2 100,j3 100, j4 100, j5 350, j6 150/;

Binary variable x(i,j) 'if AMR i is assigned to route j';
```

```
Variables
    x(i,j) if AMR i is assigned to route j
   z


Equation

   total 'objective function'
   capacity 'capacity constraint'
   allocation 'each robot can be only assigned to one route'
   battery 'battery usage costraint'
   totalAMR 'make sure all AMRs assigned';

total ..           z =e= sum((i,j), x(i,j)*u(i,j));

capacity(j) ..     sum(i, x(i,j)*c(i)) =g= r(j);

allocation(i) ..   sum(j, x(i,j)) =l= 1;

battery(i) ..      1 - sum(j, x(i,j)*t(i,j)) =g= b(i);

totalAMR ..     sum((i,j), x(i,j)) =e= 7;

Model transport / all /;

solve transport using MIP maximizing z ;
Display x.l, x.m;
```

Appendix 6. Scenario 1 and scenario 2 statistics.





Appendix 7. Project finance[6]

			Project Timeline																																													
	Year		2023					2024												2025												2026												2027					
	Month		Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
AS IS	Salary of Workers	(x1000 EUR)	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6
	AMR Maintenance	(x1000 EUR)	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
	Total Costs	(x1000 EUR)	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6	14,6
	Cumulative Costs	(x1000 EUR)	14,6	29,2	43,8	58,4	73,0	87,6	102,2	116,8	131,4	146,0	160,6	175,2	189,8	204,4	219,0	233,6	248,2	262,8	277,4	292,0	306,6	321,2	335,8	350,4	365,0	379,6	394,2	408,8	423,4	438,0	452,6	467,2	481,8	496,4	511,0	525,6	540,2	554,8	569,4	584,0	598,6	613,2	627,8	642,4	657,0	671,6	686,2
TO BE	Trolley Standardization	(x1000 EUR)	110,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Licencing & Programming	(x1000 EUR)	2,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Software Ecosystem Work	(x1000 EUR)	8,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Project Team Cost	(x1000 EUR)	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	System Maintenance	(x1000 EUR)	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
	AMR Maintenance	(x1000 EUR)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
	Salary of Workers	(x1000 EUR)	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,3
	Total Cost	(x1000 EUR)	148,7	27,7	27,7	27,7	27,7	27,7	27,7	27,7	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8	8,8
	Cumulative Costs	(x1000 EUR)	148,7	176,4	204,1	231,8	259,5	287,2	314,9	342,6	351,4	360,2	369,0	377,8	386,6	395,4	404,2	413,0	421,8	430,6	439,4	448,2	457,0	465,8	474,6	483,4	492,2	501,0	509,8	518,6	527,4	536,2	545,0	553,8	562,6	571,4	580,2	589,0	597,8	606,6	615,4	624,2	633,0	641,8	650,6	659,4	668,2	677,0	685,8
	GAP	(x1000 EUR)	-134,1	-147,2	-160,3	-173,4	-186,5	-199,6	-212,7	-225,8	-220,0	-214,2	-208,4	-202,6	-196,8	-191,0	-185,2	-179,4	-173,6	-167,8	-162,0	-156,2	-150,4	-144,6	-138,8	-133,0	-127,2	-121,4	-115,6	-109,8	-104,0	-98,2	-92,4	-86,6	-80,8	-75,0	-69,2	-63,4	-57,6	-51,8	-46,0	-40,2	-34,4	-28,6	-22,8	-17,0	-11,2	-5,4	0,4
	ROI (in months)		47,0																																												

[6] The salary numbers do not represent existing company data. For the research purpose, the salary data have been collected from Statistics Estonia website

Appendix 8. Scenario 3 video