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Non-functional requirements and their impact on AGV based systems

A mixed-method study on the impact of Non-functional requirements on AGV based systems

Master's thesis in Computer Science and Engineering
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Abstract

The use of Automated Guided Vehicles (AGVs) has grown rapidly in recent years. The global market was valued at 3.81 billion USD in 2021 and is expected to grow at a compound annual rate of 10.2% between 2022 and 2030. The efficiency of these systems in warehouses and production facilities are impacted by the choice of non-functional requirements (NFRs).

This study is based on a mixed-method approach to assess the impact that these NFRs have on system throughput, and whether the results differentiate based on the layout and the fleet size of the system. An interview study and a literature review were conducted to ascertain what the most essential requirements are for those systems. The results show that requirements regarding safety and robustness are the most imperative for the industry.

A simulation tool was created during the study which utilizes a modification of the A^* algorithm, based on both space and time. The tool was used to create two different layouts, used to represent different warehouse scenarios. A smaller layout (75m x 75m) and a larger layout (150m x 150m) was created. The identified NFRs were then independently varied and compared to a base case.

The results show that the identified NFRs have a profound effect on system throughput. It was established that the impact of the different NFRs generally are amplified in the smaller layout. Decreasing the fleet size leads to a larger, relative decrease in throughput for the smaller layout due to increased congestion. Increasing the fleet size has diminishing returns until the system is at max capacity and a further increase in the number of agents only leads to more congestion, lowering the throughput.

Keywords: Requirements Engineering, Non-functional requirements, Automated Guided Vehicle, AGV, Safety, Robustness

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Contents

List of Figures	xiii
List of Tables	xv
1 Introduction	1
1.1 Problem Description	1
1.2 Purpose	3
1.3 Research Questions	3
1.4 Significance of the study	3
1.5 Thesis outline	4
2 Background	5
2.1 AGV systems	5
2.1.1 Means of navigation	5
2.1.2 Control systems	6
2.1.3 Core AGV tasks	6
2.2 Path-finding algorithms for AGV systems	8
2.2.1 Dijkstra’s algorithm	8
2.2.2 Heuristics	9
2.2.3 The A* algorithm	9
2.3 Non-functional requirements	10
2.3.1 Efficiency	10
2.3.1.1 Communication	10
2.3.1.2 Computational time	11
2.3.1.3 Memory allocation	11
2.3.2 Reliability and Availability	12
2.3.2.1 Reliability in AGV systems	12
2.3.2.2 Maintenance	13
2.3.3 Robustness	13
2.3.3.1 Single point of failure	14
2.3.3.2 Deadlocks in AGV systems	14
2.3.4 Safety	15
2.3.4.1 Safety Standards	15
2.3.4.2 The Machinery Directive	15
2.3.4.3 EN 1525:1997	16
2.3.4.4 ISO 3691-4:2020	17

2.3.5	Scalability	18
2.3.5.1	Scalability in AGV Systems	18
2.3.6	Security	19
2.3.6.1	Security in AGV systems	19
2.3.7	Usability	20
2.3.7.1	Usability in AGV systems	20
2.3.8	State of the art	21
3	Literature Review	23
3.1	Related Work	23
3.1.1	Efficiency	23
3.1.2	Reliability and availability	24
3.1.3	Robustness	25
3.1.4	Safety	25
3.1.5	Scalability	27
3.1.6	Security	27
3.1.7	Usability	28
3.1.8	Existing gaps in knowledge	28
4	Methodology	31
4.1	Literature review	32
4.1.1	Search strategy and analysis	33
4.2	Interview study	34
4.2.1	Data collection	34
4.2.2	Data analysis	36
4.3	Simulation study	37
5	Results	41
5.1	Literature review	41
5.2	Interview study	44
5.3	RQ1: Essential requirements	48
5.4	Results from the simulations	55
5.4.1	Layout 1: 150m x 150m	55
5.4.2	Layout 2: 75m x 75m	57
5.5	Statistical significance	60
6	Discussion	63
6.1	Research question 1	63
6.2	Research question 2	64
6.3	Research question 3	66
6.4	Generalizable experiences	67
6.5	Threats to validity	68
6.5.1	Conclusion validity	68
6.5.2	Internal validity	69
6.5.3	Construct validity	70
6.5.4	External validity	70

7 Conclusion	73
7.1 Future work	74
Bibliography	75
A Interview Guide	I

List of Figures

1.1	Example AGV system in a warehouse setting.	2
2.1	Example of a centralized AGV system.	7
2.2	The Machinery Directive	16
4.1	Overview of the research process	31
4.2	An illustration of the 3D-A* where z-axis represents the time.	38
4.3	Overview of the final parameters of the simulation divided into five categories.	39
5.1	Overview of the thematic coding board from Miro	45
5.2	Visualization of the affinity diagram. Link	45
5.3	Total system throughput deviation from the base case given each parameter (Layout 1 - 150m x 150m).	57
5.4	Total system throughput deviation from the base case given each parameter (Layout 2 - 75m x 75m).	59

List of Tables

2.1	Calculated frequencies of AGV subsystem failures according to [1]. . .	13
2.2	Throughput of the system using corrective or corrective and predictive maintenance [2].	13
2.3	ISO 3691-4:2020, Examples of requirements for speed control.	18
4.1	Search terms and related sources	34
4.2	Roles of interview subjects	35
5.1	Analysis table for literature review. Continued on the next page . . .	41
5.2	Planguage table for frequency of loading failures	49
5.3	Planguage table for recovery time after loading failures	50
5.4	Planguage table for frequency of obstacles in vehicle path	50
5.5	Planguage table for manual recovery after obstacle in vehicle path . .	51
5.6	Example of planguage requirement for safety	51
5.7	Requirement regarding speed control for agent. Distance to object(s) is 2 tiles	52
5.8	Requirement regarding speed control for agent. Distance to object(s) is 3 tiles	53
5.9	Requirement regarding speed control for agent. Distance to object(s) is 1 tile	53
5.10	Requirement regarding the rated speed for an agent. The rated speed is set at 2 m/s	54
5.11	Requirement regarding the rated speed for an agent. The rated speed is set at 1 m/s	54
5.12	Requirement regarding the rated speed for an agent. The rated speed is set at 3 m/s	55
5.13	Simulation results based on each factor, Layout 1 (150m x 150m) . . .	56
5.14	Simulation results based on each factor, Layout 2 (75m x 75m) . . .	58
5.15	Shapiro-Wilk test results per parameter after 5 iterations. ($p > \alpha(0.05)$ -> Assumes normal distribution)	60
5.16	Paired t-test results per parameter after 5 iterations. ($p < \alpha(0.05)$ -> Statistically significant)	61

1

Introduction

The following chapter is divided into five sections and serves to introduce the research. The first section aims to provide the reader with a problem description for the research. The second section seeks to explain the purpose of the study followed by the third section containing the research questions that the thesis aims to explore. The fourth section aims to investigate the significance of the study and finally, the fifth section is a thesis outline.

1.1 Problem Description

Automated Guided Vehicles (AGVs) in the context of this thesis are autonomous robots capable of transporting goods or material, commonly in a production facility or a warehouse. They navigate with the help of sensors, lasers, and either reflexive coils or tracks in the floor of such facilities [3]. AGVs form a large and important part of modern logistics and transport systems [4]. Their use has grown rapidly in recent years, and the market is expected to be worth around 9.38 billion USD by 2030 [5]. Core tasks for AGV systems include task allocation, localization, path-planning, motion-planning, and vehicle management [4]. Depending on the allocation of intelligence in the system, they are either centralized (controlled by a central controller) or decentralized (each vehicle makes decisions independently) [4]. According to Ryck et al. [4] most modern systems are centralized. There are several ways to measure the effectiveness of such a system. Among the most widely used measurements, is the system throughput [4, 6, 7]. This is a metric that refers to the number of units delivered within a specified time period.

The throughput of an AGV system is impacted by various factors, such as; the choice of algorithms for path- and motion-planning and their computational effort, the size of the AGV fleet and warehouse layout, etc. These factors themselves are also impacted by the choice of non-functional requirements (NFRs). These are requirements pertaining how well a system must perform its functions. They could take the form of properties or characteristics that the system must exhibit or constraints to which it must comply. For example, safety directives issued by the European Union are mandatory to follow if products are to be sold within the union. This entails safety NFRs regarding collision avoidance, speed limits, etc. Requirements regarding the reliability of the system could entail NFRs regarding the uptime and mean time between failures for the vehicles. All of these NFRs ultimately impact the throughput of the system. However, the field of AGVs has yet to discuss the impact of NFRs

1. Introduction

and be studied in the context of requirements engineering. This has been done more thoroughly in adjoining fields, such as Automated Vehicles (AVs). For example, Ryck et al [4] mentions issues regarding scalability, robustness, and flexibility for centralized AGV systems, but does not measure their impact nor investigate these factors from a requirements engineering standpoint. Research conducted by Javed et al [8] investigated security aspects, but once again from a more general perspective.

As mentioned above, the throughput of an AGV system is impacted by factors such as warehouse layout and fleet size. Therefore, determining that impact in combination with a set of NFRs is of interest due to the fact that the choice of NFRs and the properties of the system will be impacted differently in differentiating scenarios. This thesis will simulate different scenarios and present them in order to fulfill the upcoming objectives.

The objectives of this thesis are as follows:

1. Explore essential non-functional requirements for AGV systems in a warehouse setting
2. Evaluate the impact that the identified non-functional requirements have on the throughput of a system.
3. Evaluate the impact that the different identified non-functional requirements have in specific, real-world alike scenarios through simulation.

Through this research, we hope to contribute to the understanding of the impact of non-functional requirements in AGV systems and provide practical insights and recommendations for optimizing the usage of these algorithms in real-world scenarios.

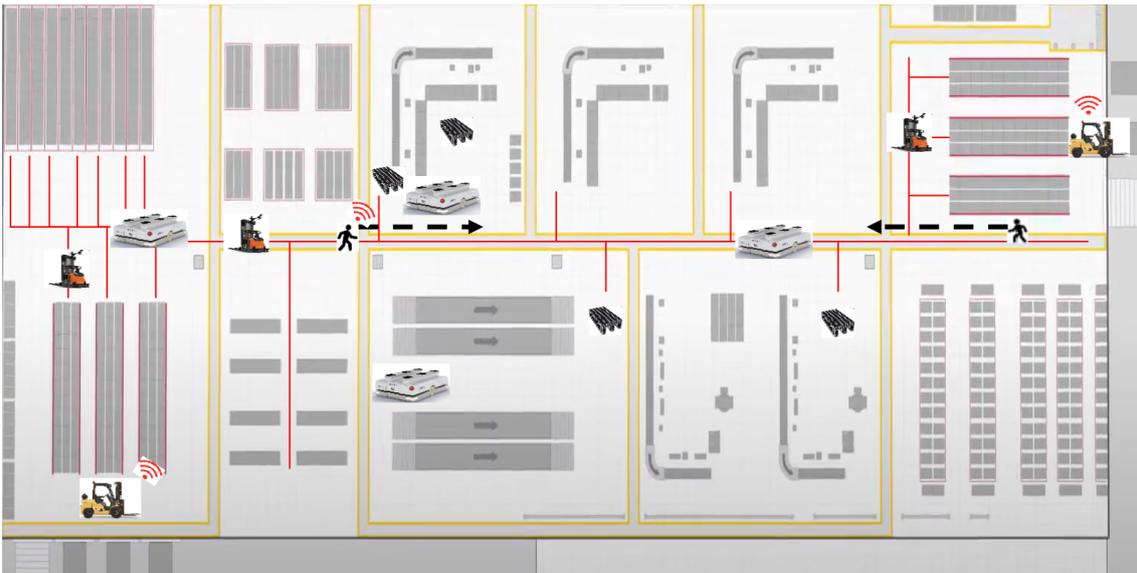


Figure 1.1: Example AGV system in a warehouse setting.

1.2 Purpose

The purpose of this study is to examine the necessary requirements for an Automated Guided Vehicle (AGV) system in a warehouse environment and how they influence the throughput of the system in different scenarios. The study will identify the essential non-functional requirements for AGV systems, and assess the impact of these requirements on the throughput. Additionally, we will validate our findings by demonstrating the impact of a set of real-world scenarios given a set of different non-functional requirements. The research aims to enhance our understanding of AGV systems design and optimization in warehouse settings.

Overall, the purpose of this study is to enhance our knowledge of AGV systems within a warehouse setting in regard to NFRs and their impact on the system throughput. The target audience for the thesis is industrial practitioners and researchers within the general field of AGVs (Not only warehouse-related).

1.3 Research Questions

RQ1: *Identify essential non-functional requirements for AGV systems within a warehouse setting.* What are the essential requirements needed to ensure the functionality of the system according to the stakeholders and literature?

RQ2: *Evaluate the impact of the non-functional requirements found in **RQ1** on the system throughput.* How does each non-functional requirement from **RQ1** affect the system throughput?

RQ3 : *Evaluate the impact of the non-functional requirements found in **RQ1** on the system throughput given a set of specific, real-world scenarios.* Given the results from **RQ1**, do differences in warehouse layout and fleet size impact the throughput?

1.4 Significance of the study

The growing importance of AGVs in warehouses and production facilities establishes a need to assess how different NFRs impact their effectiveness (throughput). Little research has been done on this subject. The objectives of the study are to explore the essential NFRs for AGV systems and evaluate their impact on the throughput on different warehouse layouts and fleet sizes. By doing this, the research will provide practical insights and recommendations that are relevant to logistics companies, as well as researchers and practitioners in the field of robotics and automation. The study's result could also have broader implications by contributing to improving the efficiency and effectiveness of such systems in general.

1.5 Thesis outline

The thesis is structured as follows:

1. **Introduction:** This chapter aims to introduce the research by providing a problem description, a purpose, research questions, the significance of the study, and lastly a thesis outline.
2. **Background:** This chapter aims to introduce relevant background information for the research. Sequentially it will introduce the topics of AGVs, path-finding algorithms, and NFRs.
3. **Methodology:** This chapter explains the methodology used to conduct the research. It starts with explaining the overall methodology. After that, it defines how the literature review, interview study, and the simulation model were created.
4. **Literature review:** This chapter contains literature that was deemed to be of interest to the study.
5. **Results:** This chapter will present the result of the interview study and the literature review used to answer **RQ1**. Sequentially, it will present the NFRs that will be used for **RQ2** and **RQ3**. After that, results for **RQ2** and **RQ3** will be presented together with some tests for the statistical power of the results.
6. **Discussion:** In this chapter we will discuss the findings of the study and common validity threats.
7. **Conclusion:** This chapter contains the authors conclusions regarding the research.

2

Background

The following chapter is divided into three sections. The first section aims to give the reader a basic understanding of how centralized AGV systems work in general. The second section aims to explain the underlying theory behind the path-finding algorithm used for the simulation tool. The third section aims to give the reader insights into the topic of non-functional requirements (NFRs) and their role in the context of AGV systems.

2.1 AGV systems

AGVs are automated, driverless vehicles used in industry and intralogistics [4, 3]. AGVs perform a range of tasks ranging from processes for handling goods and materials in warehouses, to the use as means of transportation[3]. The global market for AGVs was valued at 3.81 billion USD in 2021 and is expected to expand at a compound annual growth rate of 10.2% between 2022 and 2030 [5].

2.1.1 Means of navigation

In order to navigate through their surroundings, AGVs use different navigational procedures [3]. There are AGVs that navigate using physical guidelines, anchoring points on the floor, and laser navigation. There are several common versions, among them:

- *Inductive guidance tracks*, in which a current bearing conductor is set to the floor. The layout of the warehouse system is divided into sections that can be switched on and off. Two coils are mounted under the vehicle, inducing a flowing current. The differential in the current between the coils is a measure of the deviation from the guidance track, which guides the motor using negative feedback [3].
- *Passively inductive guidance tracks*, in which a 5-10 cm wide metal strip is affixed to the floor. A sensor on the vehicle detects the metal strip and uses this to guide the motor [3].
- *Optical guide tracks*, in which a colored strip, distinctive from the floor is painted. A camera on the vehicle uses edge detection algorithms to calculate guidance signals to the motor [3].
- *Anchoring points* in the floor are commonly used as representatives of free navigation spaces. The route is not physically fixed but realized virtually in a

computer. To navigate, it relies on dead reckoning as well as using the anchor points, usually magnets or quasi-active transponders, to take bearings [3].

- *Laser navigation* is the most prominent representative of free navigation. Retro-reflecting foil is mounted on walls and pillars and can be read precisely and at great distances using a rotating laser scanner on the vehicle. The scanner continuously scans its surroundings and measures the positions of the fixed reflectors [3] which in turn helps calculate its own position accurately.

2.1.2 Control systems

AGV systems can be centralized or decentralized, depending on the allocation of intelligence in the system [4]. A centralized system generally consists of three modules: a warehouse management system, a central controller, and a communication server [9]. The warehouse management system provides information regarding the goods, the central controller supervises the AGV by giving high-level instructions [9], and the communication server receives and transfers information between the central controller and the AGV [9]. Each AGV is allocated with a vehicle guidance control system [3]. This could be a single- or multi-board computer, or an individually designed computer based on micro-controllers [3]. The central controller receives and prioritizes tasks or orders from the warehouse management system [10]. Information regarding the location and status of the vehicle is sent from the vehicle guidance control system to the communication server which provides this to the central controller. The central controller then facilitates the selection of for example a vehicle to a certain task or a path which the AGV is to follow [10]. In a decentralized system, there is no central controller that coordinates the fleet of AGVs [11], instead, each AGV makes individual decisions based on information available to them [11].

2.1.3 Core AGV tasks

A complete AGV system consists of five core tasks to be able to operate in its environment [4, 11]. These can be seen below in Figure 2.1

The first core task is *task allocation*. A set of tasks or orders need to be optimally distributed to a set of AGVs. Task allocation is a constrained NP-hard problem, in which the total cost needs to be as low as possible. The problem can be solved in some cases by meta-heuristic optimization and other heuristics [4].

The second core task is *localization*. In this task, information about the environment is communicated to the central controller from individual AGVs. This task is often already decentralized. Information regarding the position of the AGV can be communicated on an individual level to the central controller or to neighboring AGVs [4].

The third core task, *path-planning*, is used to find the shortest path to a destination [4]. Path-planning or routing computes a basic, collision-free path using known information. It involves the representation of the free configuration space and a

graph-search algorithm to generate the shortest path, minimizing factors such as fuel consumption, travel time, and travel distance [4, 12].

Obstacles encountered during operation may require modification of the path using information about positions, goals, and static paths to avoid collisions and deadlocks, which is handled by the fourth core task, *motion planning* [4]. Algorithms for collisions, deadlock avoidance, and zone control are needed which depend on the usage of a centralized or a decentralized system [4].

Parallel to the tasks mentioned above, the fifth task, *vehicle management* controls and monitors the status of the AGVs. This could include management issues such as battery lifetime, maintenance requirements, or error status [4].

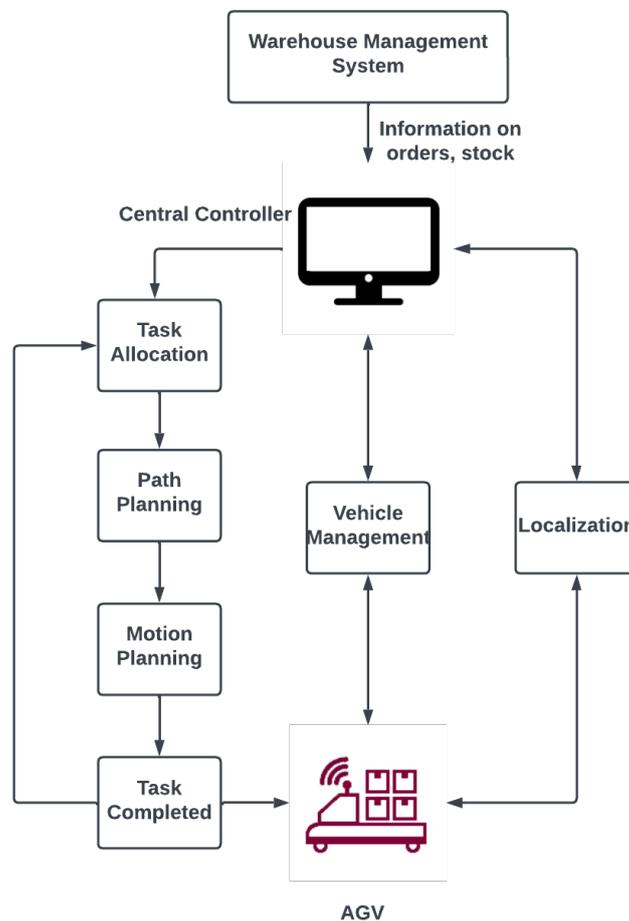


Figure 2.1: Example of a centralized AGV system.

2.2 Path-finding algorithms for AGV systems

Path-finding for AGVs refers to the index of a certain parameter (shortest path, shortest operation time), and the selection of a suboptimal or optimal path that can be connected from the location of the vehicle to the goal destination [13]. Furthermore, path-finding in an AGV system is a multi-agent path-finding problem (MAPF) [14]. The problem is such that each entity in the system should reach its goal whilst avoiding collisions [14]. A common requirement for such problems is to minimize the sum of costs of the agent's plans, which is considered an NP-hard problem. MAPF is described by [14] as:

A MAPF problem with n agents is defined by a tuple (G, S, G) where $G = (V, E)$ is an undirected graph and $S : [1, , n] \rightarrow V$ maps an agent to a start vertex and $G : [1, , n] \rightarrow V$ maps an agent to a goal vertex.

Time is discretized into time steps. For each step, t , each agent occupies one of the graph vertices. An action, a in a classical MAPF is a function $a: V \rightarrow V$ such that $a(v) = v'$ means the agent's current location is v and the next time step is v' . There are two types of actions, wait and move. A sequence of actions $\pi_i = (a_1, , a_n)$ is a single-agent plan. The number of actions in the plan defines its cost $C(\pi_i)$.

The total cost for all agents is $\sum_{i=1}^n C(\pi_i)$. A solution to a classical MAPF problem is a set of n single agent plans, which cant conflict, one for each agent, such that $\Pi = (\pi_1, , \pi_n)$. These could then be, for example, minimized $\min_{\pi \in \Pi} C(\pi)$.

2.2.1 Dijkstra's algorithm

There are several existing algorithms that solve the problem of path-finding for AGV systems. One of the fundamental algorithms, of which many others are based, is *Dijkstra's algorithm*. This algorithm solves the problem of finding the shortest path from a starting point in a graph to a destination [15]. It is described as the following by Dijkstra [16]:

Suppose we want to find the minimum total length between two given nodes, P and Q . In the course of the solution, the nodes are divided into three sets. A the nodes for which the minimum length from P is known. Nodes will be added to this set in order of increasing the minimum path from P . B is the node from which the node to be added to set A will be selected. Does not belong to A themselves. C is the remaining node.

The branches are also subdivided into three sets. I is the branches occuring in the minimal paths from P to the nodes in A . II is the branches from which the next branch is to be placed in set I will be selected. III is the remaining branches.

The solution for the minimum total length can be found by iterating the following steps, first transferring node P to the set A :

1. Consider all branches r connecting the the node we just transferred to A with nodes R in sets B or C . If R belongs to B , we investigate whether the use of r gives us a shorter path than the known path in II . If not, it is rejected. If it is, we replace the corresponding branch in II . If R belongs to C , it is added to set B and branch r is added to set II .
2. Every node in B can be connected to P in only one way if we restrict ourselves to branches from I and one from II . Each node in B has a distance from P : the node with the minimum distance is transferred from B to A , and the corresponding branch is transferred from II to I . After this, we return to step 1 and repeat until the goal node Q is in A , giving us the solution.

2.2.2 Heuristics

The heuristic function $h(v)$ directs the search in path-finding. It's a function that estimates the distance from a given node v to the destination node [17]. Heuristics that does not overestimate the true distance to that goal node is called admissible heuristics [17]. There are several well-known heuristic functions, among them Manhattan, Euclidean, and Chebyshev distance.

The Manhattan distance calculates the true distance to the goal node, given that there are no obstacles [17]. It is a geometric term used in geometric space to indicate the absolute wheelbase on the standard coordinate system between two points [18]. Given two coordinates, (x_1, y_1) and (x_2, y_2) . It is described by Li et al. [18] as:

$$h(n) = |x_1 - x_2| + |y_1 - y_2|$$

The Euclidean distance refers to the real distance between to points in the m -dimensional space, or the natural length of the vector [18]. It is the square sum of the difference between two points according to Li et al [18]:

$$h(n) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

The Chebyshev distance is a measure in the vector space [18]. The definition of the distance is the maximum of two coordinates (x_1, y_1) and (x_2, y_2) of the absolute difference of each according to Li et al. [18]:

$$h(n) = \max(|x_1 - x_2| + |y_1 - y_2|)$$

2.2.3 The A* algorithm

One of the best, known path-finding algorithms, that could be seen as an extension of Dijkstra's is the A^* search algorithm [19, 20]. Dijkstra's obtains the shortest path by traversing all nodes [19]. The success rate for obtaining the optimal paths is high, but it has a very low computational efficiency [19]. The A^* algorithm uses a combination of heuristic searching and the shortest path [20]. It has good real-time performance when the environment is not too complex [19]. Each cell in the configuration space is evaluated by the value:

$$f(v) = h(v) + g(v)$$

where $h(v)$ is the heuristic distance of the cell to the goal state and $g(v)$ is the length of the path from the initial state to the goal state, as calculated by Dijkstra's [20]. Each adjacent cell of the reached cell is evaluated by the value of $f(v)$ and the cell with the lowest value is chosen. An advantage of the algorithm is the wide range of modifications that can be done to $f(v)$ [20]. It could be modified to include different criterion's such as safety or energy consumption, thus allowing for some flexibility [20].

2.3 Non-functional requirements

Non-functional, or quality requirements (NFRs) specify how well a system must perform its functions [21]. It's a description of a property or characteristic that a system must exhibit or a constraint that it must respect [22]. The importance of this type of requirement grows as markets develop [21].

Wiegers and Beatty [22] ascertain that NFRs for embedded systems are especially critical, as the environment in which they exist is naturally more complex than pure software applications. The quality attributes that Wiegers and Beatty deem most important for such systems include: *efficiency, reliability, robustness, safety, security, and usability*. Additionally, NFRs regarding *scalability* are important in the context of centralized AGV systems due to issues with scaling for example computing power as the number of agents in the system increases.

2.3.1 Efficiency

Efficiency requirements stipulate how efficiently a system uses computer resources. Lauesen [21] defines efficiency as how fast the system responds, how much resources it uses, and how accurately it computes values. Lausen also [21] deems it to be the same as performance, whilst Wiegers and Beatty [22] agree that it's closely related, it refers to internal quality attributes rather than external.

2.3.1.1 Communication

Wireless-based solutions have become increasingly popular in the industry for controlling AGVs and managing fleets [23]. There is a necessity that the solutions provide flexibility and convenience, allowing for real-time communication between vehicles and control centers.

To ensure effective communication between AGVs and control centers, there are several standards in place, one of which is the IEEE 802.11p-2010 standard. *IEE Standard for Information Technology - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments* [24]. This standard specifies the requirements for wireless LAN medium access control and physical layer specifications, specifically for Wireless Access in Vehicular

Environments (WAVE).

The WAVE standard is designed for devices with rapidly changing physical layers and short-duration communication exchanges. WAVE applications that adhere to the standard operating in the 5.9 GHz frequency range and use seven channels with 10 MHz bandwidth each [24, 25].

To meet the requirements for WAVE applications, latency is an important consideration. Latency refers to the time delay between the initiation of a message and the receipt of its response. In the context of WAVE applications, latency is critical for ensuring the safety and efficiency of AGV operations. To address this concern, the IEEE 802.11p-2010 standard specifies maximum latency requirements for both safety-related and non-safety-related messages. Safety-related messages, which are critical for ensuring the safety of AGV operations, must have a maximum latency of 100 ms [25]. Non-safety-related messages, which are typically used for monitoring and reporting purposes, must have a maximum latency of 300 ms [24].

2.3.1.2 Computational time

The scheduling and routing tasks for AGV systems are time critical, as they are needed to work in real-time [26]. The computational speed of these tasks is dependent on the choice of algorithms to carry them out. Furthermore, any requirement on the latency sets an upper boundary for the time allowed for computing, as any computing or algorithmic processing must be completed within the time specified by the latency requirement. An AGV system adhering to for example the IEEE 802.11p-2010 standard needs to respond within the 100 ms threshold [24]. Thus, any system adhering to the standard would also need to have a computing time lower than 100 ms. Centralized solutions are often preferred for the guarantees of finding an optimal solution [27]. This guarantee vanishes with this upper boundary, as the algorithm might not be able to search the entire solution space before running out of time, leading to the choice of sub-optimal paths to the goal destination.

2.3.1.3 Memory allocation

All embedded systems are constrained by their memory limitations. For an AGV system, this limitation is set by the hardware that is chosen for the central controller. However, the amount of memory that is consumed by the system is impacted by the choice of algorithm for path-finding, the complexity of the represented production facility, and the number of AGVs present in the system.

The space complexity is a measurement for the total usage of space by an algorithm. For the A^* algorithm, the space complexity is linear $O(n)$ as it remembers the current shortest path and costs for all visited nodes [28]. This is supported by the results in [29]. The researchers studied the performance of the A^* algorithm, as well as an improvement with an additional heuristic, in a single robot system. The

performance was measured in terms of time and space complexity as well as the completeness and optimality of the solution. The maximum number of nodes and paths the algorithm considered during the iteration of a correct path was used to determine the space complexity. The results showed that these grew linearly as the distance to the goal was increased.

2.3.2 Reliability and Availability

Reliability requirements stipulate how long the system can run before experiencing a failure [22] while availability requirements stipulate the extent to which the users of a system's services are available when and where they are needed [22]. Reliability problems occur as a result of improper inputs, errors, hardware failures, or components not being available when need [22]. Availability is described by Wieggers and Beatty [22] as the ratio of uptime to the sum of uptime and downtime, we will treat it as a product of reliability, and therefore address both in the same chapter.

2.3.2.1 Reliability in AGV systems

There are different ways to assess and quantify reliability. A common measurement used in reliability and risk assessment is the failure rate (λ) [30]. Another metric, used to represent an index for repairable units, is the mean time between failures *MTBF* [30].

$$\text{MTBF}(\theta) = \frac{\text{Operating time}}{\text{Number of Failures}}$$

$$\text{Failure rate}(\lambda) = \frac{\text{Number of Failures}}{\text{Operating time}}$$

Reliability is a measure of the probability of successful performance of the system over a period of time [30]. The reliability of most component families follows the "reliability bathtub" curve [30]. This is a curve that can be divided into three different phases. Firstly, the failure rate is reduced as weak components are eliminated. In the second phase, the failure rate will remain approximately constant. In the last phase, the failure rate increases as components wear out. Assuming a component is in the second phase, with approximately constant failure rate, the reliability $R(t)$ at time t can be represented by the following equation [30]:

$$R(t) = e^{-\lambda t}$$

If we integrate this, it will give us reliability for a specified time period

$$R(t) = \int_0^t e^{-\lambda t} dt$$

The effectiveness of an AGV system relies heavily on its reliability and availability [2]. Yan et al. [1] studied reliability modeling of a single AGV system using a combined fault tree and Petri net approach. The failure rates for different components in an AGV system can be seen in table 2.1 below. The results suggest that the accumulated failure rate for all subsystems of an AGV during an entire year would be 10.45.

Table 2.1: Calculated frequencies of AGV subsystem failures according to [1].

Subsystem	Failure rate (frequency/year)
Drive unit	1.50
AGV software control system	6.00
Laser navigation system	0.88
Safety Systems	0.38
Attachments	1.25
Brake system	0.20
Steering system	0.25

2.3.2.2 Maintenance

Maintenance of the AGVs is a key factor that affects the reliability of the system. There are various maintenance strategies available, such as corrective and preventive maintenance [2]. Corrective maintenance involves repairing an AGV only when it has malfunctioned or stopped working [2]. On the other hand, preventive maintenance refers to scheduled maintenance that is carried out regularly, regardless of the current condition of the AGVs. In the study conducted by Yan et al. [2] the repair time for a vehicle during corrective maintenance was described by a normal distribution. If there was another vehicle being worked on, it would wait in a queue. Preventative maintenance was described as a vehicle health check for a predefined amount of time. The result from the study conducted by Yan et al. [2] can be seen in Table 2.2; T denotes the time interval for periodic maintenance; P the percentage of AGVs failed within the time interval; N1 the number of missions completed per year with periodic but without corrective maintenance; N2 the number of missions completed per year with both.

Table 2.2: Throughput of the system using corrective or corrective and predictive maintenance [2].

T	P	N1	N2
7 days	0,03	11518	11840
20 days	1,10	13213	14709
1 month	3,93	12840	15264
2 months	18,06	11028	15792
3 months	36,62	9372	15972
4 months	53,37	7983	16059
6 months	77,34	6084	16142
12 months	98,06	3282	16234

2.3.3 Robustness

Robustness requirements stipulate how well a system responds to unexpected operating conditions [22]. Robustness is the degree to which the system continues to function properly when confronted with invalid inputs, defects in hardware or

software components, or unexpected operating conditions [22]. A closely associated term with robustness is fault tolerance.

2.3.3.1 Single point of failure

The design and control of AGVs involve many potential technical issues which need to be addressed, among them path-planning [31].

A problem related to robustness in centralized AGV systems is the fact that the central control unit acts as a single point of failure [4]. The central control unit requires centralized, global information, shared memory, and synchronization mechanisms. It has high communication demands and a low level of tolerance towards fault conditions [32]. If there is any failure or malfunction in the central control unit it can cause the entire system to shut down, leading to delays. The need for constant communication between the central control unit and individual AGVs poses a threat to the robustness of the system if it is experiencing technical issues or network problems. The result of this could be that the AGVs stop or deviate from their intended path.

2.3.3.2 Deadlocks in AGV systems

An unexpected operating condition that impacts the robustness of AGV systems is deadlock situations [4]. A deadlock is a situation where an AGV has no possible action to take [4]. Deadlocks are caused by AGVs competing for or sharing limited resources in a system [33]. When they occur, material (such as pallets) and vehicle flows are blocked until a recovery procedure can be performed. This may result in low throughput, loss of control, congestion, or force a shutdown of the entire system [33].

The deadlock situations are handled by motion-planning algorithms [4]. When such situations occur, the motion planner usually handles this by modifying and rerouting from the path that was determined by the path-finding algorithm. All central optimizing controllers are time-consuming and lack robustness and flexibility. This is due to the fact that they only detect deadlocks moments before they occur, after which they attempt to resolve it [4].

Another tool for deadlock prevention is more proactive. Deadlocks can be avoided by limiting the number of vehicles in a particular area, called zone control [4]. How this is implemented varies [33]. The general rule, however, is to break up the production layout into zones. Only one vehicle may occupy a particular zone at one time [33]. If a vehicle approaches an occupied zone, it will stay in its current zone until the next zone is unoccupied. If such a rule is implemented, the throughput rate of the system depends on the size of each zone, with a bigger zone lowering the rate [34]. Typically, the minimum size of a zone is equal to the time required to stop an AGV from its top speed through the use of a controlled braking mechanism. Deadlocks in AGV systems are mostly the result of the zone-partitioning strategy

used within the system [34].

2.3.4 Safety

Safety requirements deal with the need to prevent a system of any kind from doing injury to people or property [22]. Safety requirements are often dictated by government regulations, and legal or certification issues are important to consider [22].

2.3.4.1 Safety Standards

Standards are a set of guidelines, procedures, and specifications that have been established to provide a framework for consistent and reliable performance in various industries. They are used for different purposes in requirements, ranging from mandatory to voluntary adoption, and they play a crucial role in ensuring that products, services, and systems meet the required quality, safety, and environmental standards.

In some cases, standards are mandatory and act as constraints for the system [21]. In such instances, adherence to these standards is essential, and any deviation from them could have adverse effects on the system's performance, reliability, and safety. It is therefore imperative that such mandatory standards are not omitted when considering requirements. In contrast, voluntary standards are followed at the discretion of organizations or individuals. While they are not legally binding, they provide a framework for best practices [21].

Technically, standards can be proposed by any organization, but internationally, the largest organization for standardization is the International Organization for Standardization (ISO). ISO develops and publishes international standards that are recognized globally, covering various industries and sectors. In Europe, the main body for standardization is the European Committee for Standardization (CEN), which works closely with ISO to develop and promote standards that are specific to the European Union (EU) and its member states.

CEN produces European Standards (EN). They come in two different types, non-harmonized ENs, and harmonized ENs. The former refers to voluntary standards while the latter refers to a specific category of standards that are used to prove that products comply with the technical requirements of EU law [35]. Whilst the harmonized standards could be considered voluntary, the technical requirements that they comply with are mandatory [35].

2.3.4.2 The Machinery Directive

The Machinery Directive, which governs machinery, interchangeable equipment, and safety components among other products is the underlying EU directive relevant to

AGVs [36]. This directive makes up the technical requirements that are mandatory to follow. In order to demonstrate compliance with the directive in the context of AGVs, there is a harmonized EN. It's called EN 1525:1997, *Safety of industrial trucks - Driverless trucks and their systems* [37]. There is also an ISO standard, ISO 3691-4:2020, which is slated to replace EN 1525:1997 but has not yet been harmonized.

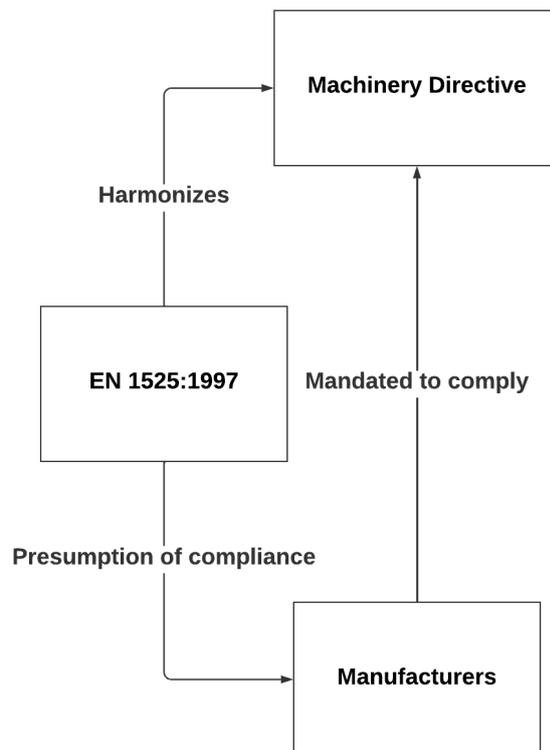


Figure 2.2: The Machinery Directive

2.3.4.3 EN 1525:1997

EN 1525:1997 proposes requirements regarding the safety of AGVs [37]. The standard encompasses a wide range of subjects, some of which has an impact on the path-finding algorithms of an AGV system and some which lies beyond that scope. The standard requires that AGVs are designed and operated to ensure safe movement, taking into account the specific application and operating conditions [35]. The AGVs must be equipped with appropriate sensors to avoid collisions [37]. It requires a risk assessment to be made in order to identify potential hazards for the specific system [37]. This assessment should consider factors such as the speed of the AGV, the layout of the facility and the presence of other vehicles or personnel operating within the environment [37]. The responsibility to implement this lies on

the system designer and operators [37].

2.3.4.4 ISO 3691-4:2020

ISO 3691-4:2020 or also *Industrial trucks - Safety requirements and verification - Part 4: Driverless industrial trucks and their systems* has been established by ISO with the intention to align with major legislative regulations in the EU, Japan, North America and Australia [38]. It is a C-type standard, which means it concerns safety standards detailing safety requirements for a group of machines [39]. In the context of path-finding algorithms, requirements regarding speed control and braking is of interest. All systems adhering to the standard must have a personnel detection system, i.e sensors that can detect objects or personnel within a certain distance from the truck. This distance may vary depending on the specific application and type of system that's being used [38].

The standard stipulates that the AGV has to stop in the range of personnel detection means for the worst condition specified by the manufacturer, as a function of speed, friction, gradient, and rated load. Furthermore, it should be able to stop before contact is made between the rigid parts of the AGV or its load and a stationary person. In the case that the AGV has stopped due to an object within its path, it can be restarted after a minimum delay of two seconds [38].

The speed control of the system should follow the requirements specified in Table 2.3, among others [38]. The requirements differ depending on whether the personnel detection sensors are activated or muted and the distance to objects within the AGV's surroundings. The standard does not explicitly stipulate a maximum speed limit. Any system complying with the standard, however, should have a speed that is lower than the rated speed for the system [38]. This is the travel speed as defined by the manufacturer [38]. As an example, Toyota's current AGV solutions have a maximum speed ranging between 2,0 - 2,2 m/s [40].

Table 2.3: ISO 3691-4:2020, Examples of requirements for speed control.

Clearance on one side, C1	Clearance on other side, C2	Clearance from object in direction of travel	Personal Detection Means	Max speed
>500 mm	>500 mm	>500 mm	Active	Rated speed
>500 mm	>500 mm	>500 mm	Muted	0,3 m/s
>500 mm	>500 mm	<500 mm	Active	0,7 m/s
>500 mm	<500 mm	<500 mm	Muted	0,3 m/s
>500 mm	<500 mm	>500 mm	Active	1,2 m/s
>500 mm	<500 mm	>500 mm	Muted	0,3 m/s
>500 mm	<500 mm	<500 mm	Active	0,7 m/s
>500 mm	<500 mm	<500 mm	Muted	0,3 m/s
<500 mm	<500 mm	>500 mm	Active	1,2 m/s
<500 mm	<500 mm	>500 mm	Muted	0,3 m/s
<500 mm	<500 mm	>500 mm	Active	Rated speed
<500 mm	<500 mm	<500 mm	Active	0,3 m/s
<500 mm	<500 mm	<500 mm	Muted	0,3 m/s

2.3.5 Scalability

Refers to requirements regarding how easily the system can grow to handle more users, transactions, servers, or other extensions. Scalability has both hardware and software implications. Scaling up a system could mean acquiring faster computers, increasing network capacity, data compression, or increasing the number of producing units in a system [22].

2.3.5.1 Scalability in AGV Systems

The problem of path planning in a multi-agent environment refers to the challenge of determining the best routes for multiple autonomous agents, such as robots or vehicles, to move from their current locations to their desired destinations. This problem is notoriously difficult, and it has been proven to be NP-hard, which means that finding an optimal solution to this problem becomes increasingly challenging as the number of agents, in this case, AGVs and tasks in the system grows [41].

The number of AGVs, n , that is required for a system can roughly be estimated as the following, where T_L = total loaded travel time, T_E = total empty travel time, T_W = total waiting time and T_A = time an AGV is available [42].

$$n = \sum \frac{T_A + T_E + T_W}{T_A}$$

In current industrial AGV systems, a centralized approach is often used, where a

central unit is responsible for planning the trajectories for all AGVs simultaneously. The central unit has information about the positions, goals, and static paths that the AGVs must follow [4]. It uses this information to search the solution space for an optimal solution while ensuring that the planned trajectories are collision-free and deadlock-free. However, this centralized approach becomes less scalable as the number of AGVs and the environment size increases, as the computational requirements increase exponentially [4, 43]. This can lead to increased response times and decreased system performance, limiting the number of AGVs that can be used in the system.

Fransen et al. [44] ascertains that a system is deemed scalable if it can hold a one-to-five zone and AGV ratio. A zone is represented by a cell in a grid-based layout. This layout is not supposed to represent a physical system layout, but rather a virtual grid representation of the layout to control the AGVs. Only one AGV can be present in each zone at any given time. This implies that the scalability also relies on the layout of the production facility. A higher amount of grids would imply the opportunity to increase the amount of AGVs in the system to maintain the ratio. Traditional bottlenecks and traffic rules within the facility can also impact the scalability, for example, if the system allows for uni-directional or bi-directional paths or the amount of input or output stations [42].

2.3.6 Security

Security requirements deal with unauthorized access to the system [22]. The requirements could refer to physical, data, or software security. They are often based on business rules or corporate policies [22].

2.3.6.1 Security in AGV systems

When considering the security of any embedded system, it's important to consider the vulnerabilities both of hardware and software components, as they all can be compromised with respect to their confidentiality and integrity. Below are a few considerations from different standards, stipulating requirements both for the AGV itself, as well as the software controlling it.

ISO 3691-4:2020 specifies several security requirements for AGV systems, including the use of personnel detection devices, such as scanners [38]. These scanners are designed to detect people or objects, and they should be able to detect objects of different sizes and shaped [38]. Interlocks or other means should also be used in accordance with the standard to prevent unauthorized access to the AGV's power source or control systems to prevent hazards [38]. The standard also emphasizes that AGVs should be operated only by authorized personnel who have received adequate training on the safe use of the AGV [38].

ISO/IEC 27001:2013, *Information technology Security techniques Information security, management systems Requirements* is an information security management

standard that provides a comprehensive framework for managing and protecting sensitive information, not specifically tailored towards AGV systems [45]. It includes requirements and guidelines that can be applied to AGV systems, however, organizations should conduct a risk assessment to identify potential security threats and vulnerabilities and develop a plan to mitigate them [45]. Organizations can also implement access controls such as password authentication, biometric authentication, or the use of access cards, which can help prevent unauthorized access to the AGV system [45]. Measures can be taken to protect sensitive data from unauthorized access or modification [45]. Regular security audits can be conducted to identify potential security vulnerabilities and areas for improvement, and a plan can be in place to respond to security incidents [45].

WAVE applications adhering to the IEEE 802.11p-2010 standard also should adhere to requirements in regard to the security of the data [24]. The standard specifies the use of a shared secret key for authentication, which is used to authenticate each communication between devices [24]. This ensures that only authorized devices are able to communicate over the network and that data transmitted over the network cannot be intercepted by unauthorized parties. It includes measures to protect against packet replay attacks, which involve capturing and re-transmitting packets to disrupt the communication between devices [24]. The standard specifies the use of a sequence number for each packet transmitted, which is used to detect and prevent packet replay attacks [24]. It also includes measures to protect against denial-of-service (DoS) attacks, which involve disrupting the communication between devices by overwhelming the network with traffic. The standard includes mechanisms for managing and prioritizing network traffic, which can help prevent DoS attacks by ensuring that critical network traffic is given priority over less important traffic [24].

2.3.7 Usability

Usability requirements deal with ease of learning, ease of use, error avoidance and recovery, the efficiency of interactions, and accessibility [22]. Usability deals with the efficiency of the system in regards to the users: how easy should it be to learn, how efficient should it be in daily use, etc [21].

2.3.7.1 Usability in AGV systems

Since AGVs are embedded systems, both the hardware and software parts need to be considered for usability [46]. There are several standards suggesting requirements regarding the usability of products, but there are no specific standards for AGVs. One such standard is ISO 9241-11:2018 *Ergonomics of human-system interaction Part 11: Usability: Definitions and concepts* [47]. The standard outlines the absence of negative consequences, satisfaction, and wide applicability as important for the usability of a product [47].

The absence of negative consequences means that a system, such as an AGV, should be designed in such a way that it does not cause any adverse effects or outcomes to the user, equipment, or surrounding environment [47]. An AGV adhering to ISO

ISO 3691-4:2020 suggests requirements regarding personnel detection means, braking, zones, and speed control [38]. These requirements are to be followed to ensure that the system is safe to operate and that there are no hazards to individuals or equipment, thus limiting negative consequences [38]. In an AGV system, economic harm can be caused by for example deadlock situations, as they impact the throughput of the system [33]. For larger AGV systems, the choice of path-finding algorithm and heuristics can cause sub-optimal paths when the entire solution space can't be searched [4]. Accumulated over time, this could also result in economic harm.

Satisfaction is an essential component of usability, which means that a system must be designed to ensure user satisfaction [47]. In the case of AGV systems, satisfaction can be achieved by ensuring that the system meets the user's expectations and provides a positive experience. To achieve satisfaction in AGV systems, the system must be designed to meet the needs of the user. This includes providing an interface that is easy to use and understand and allowing for easy and efficient control of the AGVs. The AGV should also be designed to perform its tasks smoothly and effectively, without causing any disruptions or delays. Furthermore, the AGV system should be designed to meet the specific needs and requirements of the user. For example, the AGV should be configured to handle the specific materials, load capacity, and travel distance required by the user's operation which would ensure that the AGV is optimized for the user's needs and provides maximum satisfaction.

Wide applicability means that a system must be designed to be applicable to a wide range of users and contexts [47]. To achieve wide applicability in AGV systems, the system must be designed to be flexible and adaptable to different environments and situations. For example, the system should be able to handle different types of loads, travel distances, and work environments. Additionally, the system should be designed to be compatible with different hardware and software configurations, making it easier to integrate with other systems.

2.3.8 State of the art

Below we will present the current state-of-the-art, regarding AGVs in the context of different NFRs.

- The current state-of-the-art safety requirements for AGVs is the ISO-3691-4:2020 standard. This standard is to replace EN 1525:1997.
- ISO-3691-4:2020 also stipulates requirements regarding the security of AGVs. This can be complemented with ISO/IEC 27001:2013 which is a general information security standard.
- The current state-of-the-art AGV systems are centralized, as a consequence of this they can have issues with scalability and robustness. The scalability of a centralized system is limited due to increasing computational requirements when the system expands. The centralized system also acts as a single point of failure and malfunctions that can lead to system shutdowns. Furthermore, the need for constant communication between the central unit and the AGVs

impacts the robustness of the system as a whole.

- Reliability studies of modern AGVs show that they have a failure rate of roughly 10,45 sub-component failures per year, which is impacted by the choice of maintenance strategy.
- There is no AGV standard for communication. The IEEE 802.11p-2010 is state-of-the-art in adjoining fields and could be applied. Depending on the level of parallelism in the system, this could set an upper limit on the computational time of any algorithms used by the system.
- There is no AGV standard for usability. However, ISO 9241-11:2018 outlines requirements for the usability of products. Usability comes according to the standard as a result of the absence of negative consequences, satisfaction with the product, and wide applicability.

3

Literature Review

The objective of the upcoming chapter is to present related works for the research. Articles from the field of AGVs will be included when such have been identified. Otherwise, it will encompass relevant academic papers from the fields of automated vehicles (AVs) and more general literature from the field of software engineering. The chapter will end with a section regarding the identified gaps in knowledge in the current literature.

3.1 Related Work

The following section will discuss different published articles in the context of AGVs when possible or AVs or other industries where generalization to AGV systems would be possible and studies in AGVs are scarce. The articles will concern the non-functional requirements regarded by Weigers and Beatty [22] to be essential for embedded systems. These include safety, scalability, robustness, reliability, availability, security, usability, and efficiency.

3.1.1 Efficiency

Tsang et al. [48] studied the problem of warehouse multi-robot automation in discrete-time and space configuration with the focus on task allocation and path-planning. A comparison between the computation times of a decentralized system using a RERAPF algorithm for path-planning and a centralized system using the conventional A^* algorithm was made, for a varying amount of tasks and robots. With the number of robots varying between 1 and 100, the results showed that the computational time for the A^* algorithm increased almost logarithmic from 0 ms to 340 ms as the number of vehicles in the system increased.

Setiawan et al. [49] conducted a comparative analysis of the A^* and $D^* Lite$ path-planning algorithms for a single-AGV system was made. The resulting simulation showed that the computing time, given that there were no unknown obstacles in the path, was 0.3 ms for the A^* algorithm and 5.2 ms for the $D^* Lite$ algorithm. However, in the case where the path had to be re-planned due to unknown obstacles, the $D^* Lite$ algorithm outperforms the A^* algorithm given that the state space is large enough.

Whilst the studies conducted by Tsang et al. and Setiawan et al. [48, 49] compare

different algorithms and their computational effort, no studies have been made that take different NFRs into account. Taking different NFRs into account could give the industry further perspective on what type of algorithms are most suitable given different contexts.

3.1.2 Reliability and availability

Sarker et al. [50] conducted a review of sensing, communication, human factors, and controller aspects for connected and automated vehicles (CAVs). The authors deemed that the human factor was important for the mass adaptation of CAVs, which largely depends on the accuracy and reliability of the vehicles. Among the critical factors regarding the reliability of the vehicles are: the level of accuracy of the vehicles' routes, availability of current roadway information, level of training and prior learning of a vehicle, system failure detection, and accuracy of the route selection.

Schöner [51] studied the challenges and approaches for testing of highly automated vehicles (HAVs). The pretext of the study was that this type of system requires high levels of availability and effectiveness. The authors deemed that systems with high-reliability requirements are designed with a functional analysis approach. Amongst the goals of this methodology is that it allows for calculating reliability on a system level based on properties in the sub-components.

Huang et al. [52] conducted a review on human-machine shared control systems for AVs. Amongst the conclusions that the authors made was that software failure detection, including component and communication failures must be addressed. They deemed it necessary to develop a control system that can detect and implement any potential fault, as the reliability of the system highly influences the driver's trust in the technology.

Yan et al. [2] investigated the impact that different maintenance strategies has on the throughput of AGV systems was investigated. More specifically, they studied the impact of corrective and predictive maintenance.

Availability and reliability in the context of AVs have different focal points than AGVs. The reliability-related issues mentioned by Sarker et al., Schöner and Huang et al. [50, 51, 52] are mostly regarding the safety of the vehicles. In the context of AGVs, the availability is a function of their reliability instead. Whilst reliability issues are connected with safety, the main concern is the impact that availability has on the throughput of the system. This issue has not been studied thoroughly, although Yan et al. [1] studied it within the context of maintenance strategies.

3.1.3 Robustness

Orf et al. [53] presents a novel method for probabilistically deriving the functionality of a localization system, a part of the AV that is deemed safety-critical. The authors deem that the high demands on safety for AVs make failure-free operation and malfunction detection necessary.

Martinez and Francesc [54] provides an overview of the current state-of-the-art in key aspects of autonomous driving. The authors ascertain the need for these systems to continue working after a failure and suggest that the support of cloud computing could help in this regard. Further, they establish the need for a cooperative environment regarding communication with other agents in the environment. In order to accomplish this they ascertain the need for a robust communication network being able to handle and transmit huge amounts of data in all possible conditions.

Li et al. [55] investigated platooning of connected and automated vehicles. Amongst the conclusions the authors made was that communication issues, quantization errors, and packet loss posed a significant challenge for the technology.

Gruyer et al. [56] studied the impact of Cooperative, Connected, and Automated Mobility (CCAM). The researchers ascertain that the capability of the technology is strongly related to the robustness of its components. Furthermore, they ascertain that for automation beyond what is available today, onboard sensors are not enough to guarantee the high requirements for robustness and reliability.

Whilst neither of the studies is researching robustness in the context of AGVs, some of the issues are similar. The importance for the system to continue working after a failure, as ascertained by Orf et al. and Martinez and Francesc [53, 54] is also important in the context of AGV systems. Current AGV systems suffer from a lack of robustness, impacting the system by 1) creating potential deadlock scenarios, 2) forcing re-planning of routes, and 3) lowering the throughput. Just as for the CCAM systems mentioned by Gruyer et al. [56], the capability or capacity of an AGV system is greatly dependent on its robustness. Evaluating robustness in the context of AGVs could help the industry by providing insights regarding its impact, and create incentives to come up with better solutions.

3.1.4 Safety

Marvel and Bostelman [57] presented an overview of safety standards for AGVs, and describe how those related to other adjoining fields in modern manufacturing. Among the safety standards discussed were the Machinery Directive and EN1525. The authors further discussed the future of such standards, and speculated that they should include criteria such as; measurement of dynamic obstacles, three-dimensional imaging to detect overhanging obstacles, detection of humans located near the AGV, and more.

Tiusanen et al [58] presented an overview of current safety requirements for AGVs

and other autonomous machines. The authors ascertain that there is a gap between the safety requirements set in standards and the current state-of-the-art in the industry. Furthermore, they ascertain that one of the largest challenges for the industry, in regard to safety standards, is the requirements for the sensor systems used to detect objects.

Javed et al [59] discusses safety assurance in the context of Industry 4.0. They ascertain that production in Industry 4.0 is to be deemed as safety critical. For example, due to the simultaneous presence of AGVs and human workers in the same site. They establish that safety requirements are derived either from a hazard analysis or extracted from a set of safety standards.

Menzel et al. [60] analyzed a scenario-based approach for the design of vehicles using the ISO 26262 standard, which represents the state-of-the-art for safety-critical electric vehicle systems. The authors deemed that automation beyond conditional automation has a large challenge in ensuring that the vehicles behave in a safe way.

Riedmaier et al. [61] conducted research resulting in a survey on scenario-based safety assessment for AVs. They consider two aspects when assessing the safety of a vehicle. Firstly, they ascertain that safe functionality must be ensured. Secondly, that the intended function, if proven safe, cannot introduce hazards caused by technical failures in the system's software or hardware. They deemed that the market of AVs will not grow unless the challenge of proving the safety of these systems to legislators and society has been solved.

Stolte et al. [62] derived safety goals and safety requirements for actuation systems of AVs in accordance with ISO 26262. They ascertained that causal factors for unsafe control actions for AVs include, among other aspects: inadequate control algorithms, inconsistent or incomplete models, missing or delayed feedback from sensors, component failures, and missing inputs. Their findings implied that measures to go beyond the current state-of-the-art will be needed to ensure the functional safety of AVs.

The studies by Marvel and Bostelman [57], Tiisanen et al. [58] and Javed et al. [59] ascertain the use of safety standards as a way to elicit safety requirements for AGV systems. Research such as the study conducted by Stolte et al. [62] would be insightful for the industry, where safety requirements are derived from a standard. This is due to the fact that ISO 3691-4:2020 has similar, demanding requirements for safety. Just like AVs, AGVs operate in environments in close proximity to humans. Therefore, as mentioned in Riedmaier et al. [61] regarding the market for AVs, AGVs have to follow these strict safety standards in order to be deemed as an option to conventional forklifts for the public.

3.1.5 Scalability

Ryck et al. [4] presents state-of-the-art control algorithms and techniques for AGV systems. The researchers look at decentralized versus centralized solutions. The authors ascertain that current, centralized solutions suffer from a lack of scalability. This indicates a need for an optimized algorithm and a low-latency decentralized solution.

Fransen et al. [44] presented a real-time path planning approach for dense, grid-based AGV systems. The authors ascertained that throughput is the key performance index for such a system. Furthermore, they ascertained the key features that an AGV system should possess. It should be flexible, applicable to different layouts, robust, and able to cope with the inaccuracies and unexpected conditions that impact the throughput. It should also be scalable, and applicable to systems with a zone-to-AGV ratio of five to one.

Duboc et al. [63] presented a goal-oriented approach for eliciting, modeling, and reasoning about scalability requirements, for software systems in general. The authors regard this type of NFRs to be one of the most important for any software-intensive system. Furthermore, they ascertain the need to define the scalability goals of a system through an a priori analysis. The authors deem that the context is important when assessing the scalability of a system. Among things to consider; are systems quality goals, the characteristics of the application domain and its variation, and the acceptable levels of quality goal satisfaction under these variations.

As mentioned by Ryck et al. [4], centralized AGV systems suffer from a lack of scalability. Among the problems identified is that the computational time increases exponentially with the number of AGVs and the size of the environment. The importance of scalability is ascertained by [63]. As this issue has been ascertained, studying it further and simulating its impact would be of value to the industry.

3.1.6 Security

Chowdhury et al. [64] conducted research regarding cyberattack surfaces and security vulnerabilities for connected and automated vehicles (CAVs). The authors recommended the following practices based on ISO 26262. Among the different vulnerabilities identified were in-vehicle systems such as sensors and software, v2x communication networks (vehicle-to-x), and attacks on the supporting digital infrastructure.

Javed et al. [65] studied the security and safety of platooning AGVs in production facilities was investigated. The authors deemed that a safety-critical system, such as AGVs, can only be considered safe if they are also secure. In light of this, they conducted two different analyses to derive safety and security requirements and simulated their results using a digital twin.

The study conducted by Javed et al. [65] is recent, exhaustive, and covers most

possible security threats. The study, even though the context is platooning AGVs in a quarry, ought to be generalizable to contexts such as warehouse settings as the threats they identified are very similar.

3.1.7 Usability

Schömig et al. [66] created a standardized test procedure for usability evaluation of external human-machine interfaces (eHMIs) in the context of automated vehicles was created. In the study, they defined procedures for creating usability requirements. The authors proposed following the usability definition provided by ISO 9241-11, that the system must be effective, efficient, and satisfying the user's needs.

Pauzie and Orfila [67] studied human factors that impact opinions regarding AVs. The authors ascertained the importance of a human-centered approach to the design of transport and automotive systems. They identified issues such as technology acceptability, situation awareness, and mental workload to be critical for the usability of AVs.

Younessi and Lauesen [68] investigated usability requirements in general. The researchers ascertained that usability can be divided into five factors; ease of learning, task efficiency, ease of remembering, understandability, and subjective satisfaction. The necessity of each factor depends on the context of the system under study.

Similar to Younessi and Lauesen [68], Bevan [69] investigated usability requirements in a more general manner. The paper focuses on "quality of use" which the authors deem to be the end goal of usability. Furthermore, the authors ascertain that usability requirements should be stated in terms of the effectiveness, efficiency, and satisfaction required in different contexts.

No studies have been made of the impact that usability requirements have on AGV systems. The studies conducted by Schömig et al. and Pauzie and Orfila [66, 67] are within the context of AVs, whilst Younessi and Lauesen and Bevan [68, 69] studied usability for software in general. However, following the standard mentioned by Schömig et al. [66] and the impact that it has on AGV systems would provide the industry with insights regarding how important such factors are. However, given the nature of the research at hand, simulations might not be the most appropriate way to investigate such factors.

3.1.8 Existing gaps in knowledge

The literature review proves that there are multiple significant gaps in current academic literature regarding the use of NFRs in the context of AGV systems, which establishes a need for such a study. Below follows a summary of the position of the existing literature in the field.

- Studies regarding NFRs in the context of AGVs are lacking. Studies exist that

consider different quality attributes, such as reliability, safety, and security. The studies that do exist on these subjects are however not considering these quality attributes from a requirements standpoint.

- No articles were identified that study several types of NFRs simultaneously in the context of AGV systems and their impact on the system throughput.
- Articles discussing safety in the context of AGVs were identified, however, they had no focus on requirements. Articles that studied safety as an NFR, in the context of AVs were identified. Two of the identified studies used the ISO 26262 standard as a baseline.
- Research in the field has concluded that centralized AGV systems suffer from a lack of scalability. However, no in-depth studies using scalability as an NFR were identified by the researchers.
- Studies have been conducted in adjoining fields regarding the robustness of CCAMs and AVs. Whilst many of the more important points made are similar, no studies have been conducted in the context of AGVs and requirements engineering.
- Reliability-related issues have been studied both in the context of AGVs and AVs. However, this has not been done from a requirements engineering standpoint.
- Studies regarding the efficiency of different path-finding algorithms used in AGV systems are common. However, no studies were identified taking different NFRs into account.
- Studies have been conducted regarding the security of platooning AGVs in a production facility. As the threats are similar to those for AGVs operating in a warehouse environment, the results ought to be generalizable.
- No studies were identified regarding the impact of usability on AGV systems. The studies that have been conducted are in the context of AVs or on a more general level.

The thesis addresses several of the gaps mentioned above. It is a study conducted from a requirements engineering standpoint on the subject of AGVs. Requirement engineering studies in this context is rare and the articles that does exist on certain subjects (safety, reliability for example) are discussed in a more general context. The study also considers several different types of NFRs simultaneously, rather than discussing them in isolation. Furthermore, it investigates the relationship between these NFRs and throughput (efficiency). During the course of the research only one such study was identified, which had a focus on reliability.

4

Methodology

In this section, we will provide an overview of the methodology we used to address the research questions posed in this study. Our approach was a mixed-methodology one, which involves the use of both qualitative and quantitative methods of data collection [70]. Specifically, we employed a non-systematic literature review, exploratory semi-structured interviews, and computer simulations to collect data.

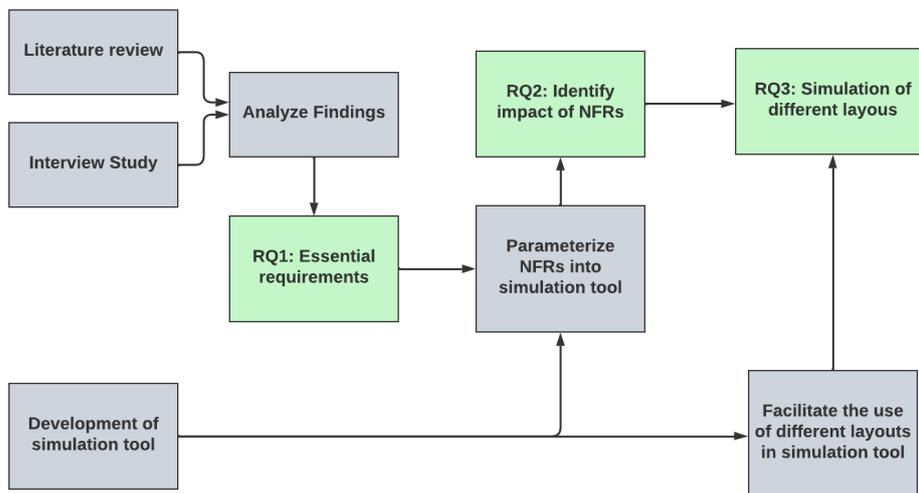


Figure 4.1: Overview of the research process

The use of qualitative research methods is particularly valuable when investigating human behavior and interactions in natural settings and data usually takes the form of text or pictures [71]. The strength of qualitative methodologies is that they force the researcher to delve into the complexity of the problem at hand, rather than abstract it away [71]. This makes the potential results of the research richer and more

informative [71]. The use of qualitative research methodologies has been shown to be useful in the field of software engineering [72].

Quantitative methods are useful when describing anything other than human behavior, using statistics or other numerical data and usually take the form of numbers or classes [72]. Quantitative data often provides a better understanding of the studied phenomenon and has been the primary data type used in software engineering research historically [72].

By employing a mixed-methods approach, we were able to take advantage of the strengths of both qualitative and quantitative methods and gain a more comprehensive understanding of the research questions at hand [70, 72, 73]. Furthermore, it made it possible to employ methodological triangulation to confirm the validity of our findings. Methodological triangulation involves the use of multiple methods to investigate the same research question, which can help to reduce the risk of bias and increase the reliability of the results [72].

4.1 Literature review

All literature reviews are more or less structured ways of collecting and synthesizing available data in regard to a specific topic [74]. Amongst the purposes for utilizing a literature review as a tool in research are identifying the gaps in knowledge and helping identify general patterns within the same area [75]. Literature reviews in general are an appropriate methodological tool when the researcher wants to evaluate theory or evidence in a certain area [74]. This could be done broadly, such as in exploring the collective evidence within the topic of interest [74].

The conducted literature review is a targeted, semi-systematic review. Being targeted implies that it will focus on specific areas of interest, rather than attempting to cover all available literature on a topic [76]. A semi-systematic literature review implies that it is not fully systematic, nor fully integrated [74] with the purpose to gain an oversight of the research area [74]. Appropriate research questions are often broad, similar to this thesis [74]. Samples from semi-structured reviews are mostly in the form of research articles and the search strategy can be more or less structured and the analysis and evaluation both qualitative and quantitative [74]. As the study is of the mixed-methodology approach, utilizing both quantitative and qualitative methods of data collection, a semi-systematic approach is appropriate. Furthermore, semi-systematic reviews are appropriate when studying a broad topic, which has been conceptualized within several disciplines, all of which might not be possible to study [74]. This is true for this thesis, as AGV systems have been studied in a wide range of disciplines from the field of robotics to logistics. The study followed the general guidelines for semi-systematic reviews as proposed by Snyder [74], and the resulting search strategy will be discussed in Section 4.1.1.

4.1.1 Search strategy and analysis

Snyder [74] ascertains that when designing a literature study, one must consider the search strategy. This implies deciding and recording search terms and databases used and that the researchers decide on inclusion and exclusion criteria for the review. This is important for transparency, and maintaining a proper thread of evidence for the reader. Furthermore, Snyder [74] ascertains that one shouldn't have strict inclusion or exclusion criteria, as this can result in missing important information on the subject.

In Table 4.1 the search terms used for finding the sources for the study are visualized, along with the articles they resulted in. The articles were found using Google Scholar and come from databases such as Elsevier, IEEEExplore or Taylor & Francis. The inclusion criteria were not limited to articles within a certain year of publication but were to be written in English. Worth mentioning is that previous research on the specific topic of non-functional requirements for AGV systems is almost non-existent and the researchers had to use alternative terms to identify relevant literature. For each search term, roughly the top twenty results appearing in Google Scholar was considered. In many cases the relevancy was deemed to be minimal, and articles were omitted. When the articles was deemed to be pertaining to the subject that was to be investigated, their abstracts were read. If they still was deemed to be of interest, they were included in the study. A visualization of the search strategy can be seen in Table 4.1.

The articles that were found during the process were used to:

1. Justify the research. The identified literature was used to identify gaps in the existing research on the field of NFRs and AGV systems. For example, whilst one article studied the impact of maintenance strategies on AGV systems, the impact of reliability on the throughput of an AGV system has not been researched.
2. It helped establish a theoretical framework by which the researchers could extrapolate requirements to answer **RQ1**. For example, different standards regarding safety were identified, which could serve as a baseline for any safety NFRs used within the research.

The analysis of the literature review followed the guidelines provided by [77]. The guideline differentiates between research questions with more subjective goals (experiences, attitudes, or perceptions) and more objective goals (effect, risk, association, or prevalence). The former will be followed in this case which implies identifying findings that help answer the research question, condensing and summarizing those, and lastly grouping them thematically, preferably in a table.

Table 4.1: Search terms and related sources

Search term or source	Search Engine	Identified source(s)	Database(s)	Total number of results
'AGV efficiency path-planning'	Google Scholar	[48]	IEEEExplore	21
'Automated vehicles safety requirements'	Google Scholar	[61], [60], [62]	IEEEExplore, Elsevier, IEEEExplore	30800
'Automated vehicles scalability requirements'	Google Scholar	[78]	IEEEExplore	1280
'Centralized AGV systems'	Google Scholar	[4]	Elsevier	7510
'Comparison of a* and d* lite'	Google Scholar	[49]	Springer	438000
'Reliability AGV'	Google Scholar	[2]	Elsevier	24000
'Reliability AV'	Google Scholar	[51]	Springer	3350000
'Reliability requirements automated vehicles'	Google Scholar	[50], [52]	IEEEExplore, IEEEExplore	16300
'Robustness automated vehicles'	Google Scholar	[53], [54]	Elsevier, Elsevier	173000
'Robustness AV'	Google Scholar	[56]	-	738000
'Safety AGVs'	Google Scholar	[57], [58], [59]	IEEEExplore, -, Elsevier	27400
'Scalability automated vehicles'	Google Scholar	[79]	IEEEExplore	94300
'Scalability requirements'	Google Scholar	[63]	Elsevier	638000
'Scalability requirements AGV'	Google Scholar	[44]	Elsevier	353
'Security requirements'	Google Scholar	[65]	Elsevier	4750000
'Security requirements automated vehicles'	Google Scholar	[64]	-	449000
'Usability requirements'	Google Scholar	[68], [69]	-, Elsevier	1340000
'Usability requirements automated vehicle'	Google Scholar	[67], [66]	Elsevier, -	3280

4.2 Interview study

According to *Building theories from multiple evidence sources* [71], interviews can be used for gathering requirements and evaluating them. The aim of interviews is to gather general information, including opinions regarding processes, products, and personal knowledge. The qualitative data in this study were collected from semi-structured interviews with individuals domain-knowledgeable in the context of AVG systems. The reasoning for the choice of semi-structured interviews is that they allow for exploratory probing on issues deemed important for the study [80]. Furthermore, semi-structured interviews have the benefit of not limiting the scope of the answers provided by the interviewees and letting information or questions arise, that the interviewees might not first have considered [80]. They are designed to not only provide the information that has been foreseen but also the unexpected. Semi-structured interviews furthermore allow the gathering of detailed data and an in-depth understanding of the topic at hand by allowing follow-up questions if required [81]. The general principle that our interview guide followed can be compared with the funnel model as described by Runeson and Höst [72]. For each topic, we started off with open questions, to then narrow them down to more specific ones. The interview guide can be found in Appendix A for further details.

4.2.1 Data collection

In order to ensure that the data collected through the interviews are valuable and appropriate, it is crucial to gain access to the right individuals [82]. This was ascertained by the choice of interview subjects, which had differing but appropriate roles within their respective organizations to provide a broader perspective on the different topics. Differing roles among the interview subjects are to be preferred

according to [72]. The roles of the interview subjects can be seen in Table 3.2. The sampling method used for the interview study was convenience sampling, i.e. the subjects were chosen based on their accessibility for the study [83, 84] since these subjects are often highly paid and hard to attain. Ideally, the study would have included more subjects. However, the reason for the low number of subjects is the same as stated above: the subjects are highly paid and hard to attain.

Table 4.2: Roles of interview subjects

ID	Role	Experience
A	Solution Architect	> 5 years
B	Director of Technology	> 20 years
C	Senior Advisor AGV solutions	> 20 years
D	Manager of Automation & Vision Services	< 5 years
E	Solution Architect & Business Analyst	> 10 years

As mentioned earlier, it is important to consider triangulation when doing research, as it increases its precision [72]. Apart from the methodological triangulation that was achieved by combining qualitative and quantitative methodologies, observer triangulation was also realized during the interview sessions. According to Runeson and Höst [72] this is achieved when more than one observer takes part in the study. During the course of the interview study, both of the researchers participated in all of the interviews.

A serious consideration when using interview studies is confidentiality, consent, and the handling of sensitive results [72]. This was achieved by informing the subjects during the process of procuring the interviews. Subjects were ensured that neither their name nor the organization that they works for was to be disclosed and that any material that was to be collected would be coded in the study. Furthermore, subjects were given the names and contact information of the researchers, as well as information regarding the research and the procedures that were to be used in the study. Since all interviews were recorded for transcription, the subjects were asked to give consent before recording each session.

Each interview started with a short explanation of the study and its purpose, in accordance to *Case study research in software engineering: Guidelines and examples* [80] which is important, as it might affect the level of participation of the subjects. After that, the focus of the first segment of the interview was the subject's experience within the context of AGV systems. This is in accordance with Galletta [81], which ascertains the importance of doing this at the start of the interview. Each interview ended with a question regarding whether the subject perceived that there was something that was missed, or if they had anything additional that they would like to add.

It is also essential that a full record of the interview is taken [75]. This was achieved via the built-in Teams recording function, which facilitated a video recording of the interviews for transcription and analysis in the later phases.

4.2.2 Data analysis

According to Runeson and Höst [72], the primary objective of analyzing qualitative data is to draw conclusions while maintaining a clear chain of evidence. This requires that the reader can trace how the conclusions and results have been derived from the data. Furthermore, it is imperative to conduct analysis concurrently with data collection, as this is the phase where new insights can be discovered and acted upon [72, 73]. Since the interviews in this study were spaced over several days, each interview was analyzed separately to gain a deeper understanding before the following interviews.

The approach used to analyze the obtained data is a thematic coding approach, or constant comparison method, as described by Seaman in *Guidelines for conducting and reporting case study in software engineering* [73]. It is a generic approach to the analysis of qualitative data and is described by Robson and McCartan [75]. Although this approach has the benefit of being flexible and generic, it is often limited to describing or exploring data [75]. However, this was not an issue in this case, as the interview study was meant to be exploratory. According to Robson and McCartan [75], coding plays a crucial role in this approach, involving identifying and recording data items that exemplify the same theoretical or descriptive idea. Each code is then broken down into smaller themes that relate to the research questions. These groupings of themes are then examined for underlying themes or explanations of phenomena [73].

The thematic coding analysis in this study was conducted in accordance with the general guidelines provided by Robson and McCartan [75]. The first step was to transcribe and re-read the data to note down initial ideas. Once that was done, initial codes and themes were generated. These steps were conducted by both of the researchers using a Miro board and simultaneously working on the same interview transcription. The approach of coding after the interview sessions is defined as post-forming [73]. An affinity diagram was created based on those codes and themes, which were then interpreted. Through providing these codes, themes, and an eventual affinity diagram, the study ought to provide a clear chain of evidence for the reader. After the interview study was completed, the themes and codes were discussed with subject E to ascertain reliable results. Worth mentioning is that the researchers believe that there was a certain degree of saturation in the results despite the number of interviews. After the third interview, a general pattern started to emerge regarding which requirements the subjects believed to be important and which were deemed less important.

4.3 Simulation study

In order to answer **RQ2** and **RQ3**, there is a need to benchmark and assess the effect of the found non-functional requirements on a system's throughput and computational complexity. Initially, the idea was to use a simulator provided by Toyota, but due to the unavailability of their proprietary source code, it was decided to create a new simulation system that met the required specifications and provided greater control for this thesis.

The primary goal of simulating AGV trucks is to create a path planner which plans routes for each agent in an AGV-based system (A warehouse). The algorithm should take into account the movements of both moving and stationary objects to ensure efficient and safe route planning. The starting point for the path planner is to create a variation of the A-star algorithm and make it based on both time and space. For simplicity in the following paragraphs, this will be referred to as **3D-A***. To achieve this, the algorithm must take time into consideration, which would enable planning the route for each AGV and avoiding collisions based on their planned paths.

In order to have a path planner to find the best routes there was a need to create a layout for the subject warehouse. The original layout for the simulation system was based on nodes and vertices in a weighted directed graph which allowed the creation of complex warehouse layouts. However, it was later changed to a grid system to enhance compatibility with the new algorithm and ease the testing and creating a proof of concept phase.

In the updated grid system, each AGV can be allocated specific grids at any given time (Depending on size, safety areas around the AGV, turn radius, etc), which the 3D-A* algorithm can then take into consideration for future planning. Once the algorithm was functional and routes could be dynamically planned it was time to move to the next step. In this step, there is a need to simulate a series of tasks that can be executed by any given AGV. These tasks will have a start location, a destination, and a time when the task can be started. In order to have these predetermined tasks, two main area types were defined. The first area type act as an inbound area for the warehouse similar to a conveyor belt, we will refer to them as "Loading areas". The other area type will be similarly referred to as "output stations" where the AGVs would finish their task.

At this point, the path planner needs to be able to process these incoming tasks in a queue-based manner. For the purpose of this study, a FIFO queue was created which could process AGVs once they were assigned a new task and required path planning. In order to use this simulation tool for this study and simulate different requirements and settings, there was a need to have control over different characteristics and parameters of the simulation. For this, a number of parameters were created and assigned as the input to the simulation tool that controlled the behavior of the path planner, the AGVs themselves, the warehouse layout, and other miscellaneous settings.

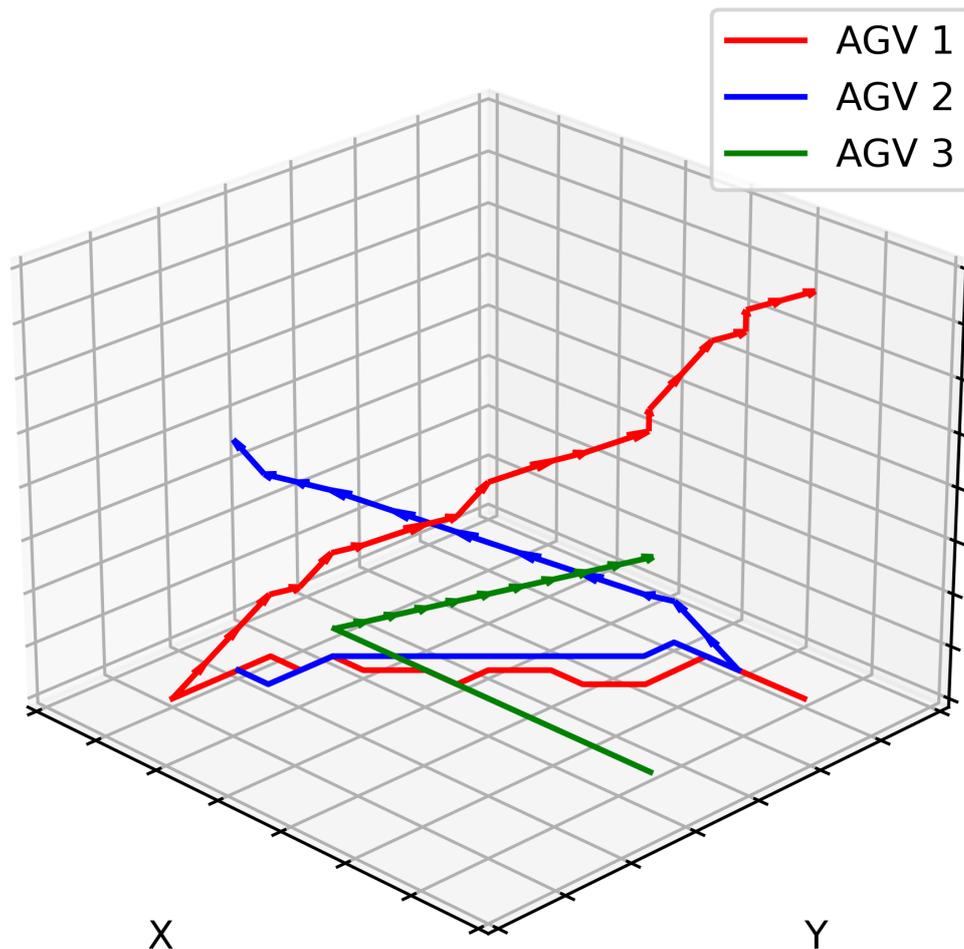


Figure 4.2: An illustration of the $3D-A^*$ where z-axis represents the time.

These parameters were divided into five different categories; Environment settings, AGV settings, Path planner settings, External factors, and debugging. The **environment settings** were used together with loading areas and output stations to create desired warehouse layouts. The **AGV settings** are mainly directed for AGVs but since speed and safety marginal are taken into consideration when path planning, these settings also affect the behavior and results of the path planner. The third category, **Path planner settings** was used for fine-tuning the heuristic and the behavior of the path planner based on the different layouts. Another important group of parameters, the **External factors** were used to create distributions to the system which often occur in the real world. These parameters were used to simulate problems during different stages of each task such as the loading/offloading stages but also during transport. Finally, some **Debugging** parameters were used for testing, debugging, and understanding the path planner's behavior.

Environment settings	AGV Settings	Path planner settings
Maximum width	Number of AGVs	Retry branching depth
Maximum length	Safety marginal	Penalty for not moving
Duration	Speed	Penalty for revisiting a cell
External factors		Debugging
Duration of handling-related Issues		Toggle visualization
Probability for handling-related Issues		Toggle 3D/2D visualization modes
Duration of transport-related Issues		Simulation speed
Probability for transport-related Issues		Manual path planning mode

Figure 4.3: Overview of the final parameters of the simulation divided into five categories.

After the simulation system was operational, it was used to visualize the system's functionality and assess whether the algorithm is functioning as intended by checking for collisions between the agents and assessing their movements. Using the simulations, it is possible to simulate various scenarios and benchmark the system's throughput based on the parameterized NFRs. This together with different warehouse layouts provide valuable insights into how these NFRs affect the AGV system's total throughput.

Using the simulation it was possible to assess the system's performance (Total system throughput) based on the given NFRs. For each NFR multiple simulations were performed in 3 different value ranges which will be discussed later in the thesis. These values reflected the **Must, Plan, Wish** ambitions of each of the parameterized NFRs. In order to answer RQ3 multiple warehouse layouts were analyzed and two layouts were created based on the main characteristics of these layouts. The main characteristics of these layouts could be interpreted as loading areas being placed around one or two edges of the warehouse while the output stations were clustered together towards the center of the warehouse. These results were then used to answer **RQ2** and **RQ3**, which will be presented in Section 5.4

In order to detect any meaningful effects from the simulations and ensure that accurate conclusions are made a series of statistical tests was performed. The data from the simulations was used in a Shapiro-Wilks test to ascertain normality. The results are normally distributed if $p > \alpha(0.05)$ and vice versa. Once the Shapiro-Wilks test was completed, a paired t-test was conducted to test for statistical significance between the base case and the result of a simulated scenario. The paired t-test in this study is done to identify which parameters lead to a statistically significant result compared to the base case. The threshold for statistical significance is $p > \alpha(0.05)$. The results for the statistical tests can be seen in Section 5.5

5

Results

In this section, we will provide the results obtained during this study. It will start with the interview study and literature review. From this a set of requirements will be created, answering **RQ1**. After that, the results from simulating **RQ2** and **RQ3** will be presented along with a short statistical analysis of the results.

5.1 Literature review

In Table 5.1 below the findings of the literature review are presented. Each row represents an article, which has a finding relevant to answering **RQ1**, a code positioning the article to a relevant NFR, and a subcode depending on the field of use for each article.

Article	Outline	Relevant findings	Code	Subcode
[60]	Scenario-based approach for the design of AVs.	Safety is critical for AV systems	Safety	Safety (AV)
[61]	Survey on scenario-based safety assessment for AVs.	Market will not grow unless safety is ensured to stakeholders	Safety	Safety (AV)
[62]	Derived safety goals and safety requirements for AV actuation systems using the ISO 26262 standard.	Safety standards used to derive NFRs. A need to go beyond current state-of-the-art.	Safety	Safety (AV)
[4]	An article discussing the current state-of-the art for AGV systems.	Current systems lack scalability, robustness, flexibility and are computationally demanding.	Scalability Robustness Efficiency	Scalability (AGV) Robustness (AGV) Efficiency (AGV)
[53]	Provides a method for probabilistically deriving the functionality of a localization system for AVs.	Failure free operation is deemed necessary for safe operation	Robustness	Robustness (AV)
[54]	Current state-of-the-art in key aspects of autonomous driving.	The authors ascertain the need for the systems to keep working after a failure.	Robustness Safety	Robustness (AV) Safety (AV)
[55]	Investigation of platooning for AVs.	Communication issues, quantization errors and packet loss poses a significant threat to the technology.	Robustness Efficiency	Robustness (AV) Efficiency (AV)
[63]	Goal-oriented approach for eliciting, modeling and reasoning regarding scalability requirements	Scalability is heavily dependant on the context of the application domain	Safety	Safety (General)

Table 5.1: Analysis table for literature review. Continued on the next page

5. Results

Article	Outline	Relevant findings	Code	Subcode
[56]	Studies the impact of the CCAM technology.	The capability of the technology is strongly related to the robustness of its components.	Robustness	Robustness (AV)
[50]	A review of sensing, communication and human factors and controller aspects for AVs.	The adaptation of the technology depends largely on the reliability of the vehicles	Reliability	Reliability (AV)
[51]	Studied challenges and approaches for testing of AVs.	The reliability on a system level is largely dependant on the properties of its sub-components	Reliability	Reliability (AV)
[52]	A review on human-machine shared control systems for AVs.	System reliability has a large influence on the trust in the technology	Reliability	Reliability (AV)
[2]	Studied maintenance strategies for AGV systems	A combination of corrective and preventative maintenance strategies has a positive impact on system throughput	Reliability	Reliability (AGV)
[48]	Studied warehouse multi-robot automation in discrete time- and space configuration, with a focus on path-planning and task allocation	The computational time for the A^* algorithm increased logarithmically with the amount of agents.	Efficiency	Efficiency (AGV)
[49]	Comparative analysis of A^* and $D^* Lite$ algorithms in a single-AGV system.	The $D^* Lite$ algorithm outperforms the A^* algorithm when the path has to be re-planned often.	Efficiency	Efficiency (AGV)
[64]	Outline of cyber-attack surfaces and security vulnerabilities for AV systems.	The authors recommended following the ISO 26262 standard.	Security	Security (AV)
[65]	Studied the security and safety of platooning AGVs in a production facility.	AGV systems can only be deemed safe if it is also secure.	Security	Security (AGV)
[66]	Created a standardized test procedure for usability evaluation of human-machine interfaces.	The authors propose using the ISO 9241-11 to evaluate usability.	Usability	Usability (AV)
[67]	A study of human factors that impact opinions regarding AVs	Ascertained the importance of a human-centered approach for the design of automotive systems.	Usability	Usability (AV)
[68]	Studied usability requirements in general.	Usability can be divided into five factors; ease of learning, task efficiency, ease of remembering, understandability and subjective satisfaction	Usability	Usability (General)
[69]	Usability requirements in general, focus on "ease-of-use".	Requirements (for usability) should be stated in terms of the effectiveness, efficiency and satisfaction required in the context	Usability	Usability (General)

Article	Outline	Relevant findings	Code	Subcode
[44]	Presented a dynamic approach for path-planning in dense, grid-based AGV systems	Ascertain that the key performance index is throughput. There is a high desirability to have systems that are capable of coping with unexpected interruptions, and that are scalable.	Robustness, Scalability	Robustness (AGV), Scalability (AGV)
[57]	Discusses safety standards for AGVs and adjoining fields	Ascertain the use of safety standards as a basis for safety requirements for AGV systems.	Safety	Safety (AGV)
[58]	Discusses safety standards for AGVs and other autonomous machines	Believes that there is a gap between existing safety standards and the state-of-the art for the industry.	Safety	Safety (AGV)
[59]	Discusses safety assurance in the context of industry 4.0 and autonomous machines such as AGVs	Ascertain that the production in industry 4.0 is to be deemed as safety-critical. Establishes that safety requirements can be derived from standards such as ISO 3691-4:2020.	Safety	Safety (AGV)

As mentioned previously, articles regarding the use of requirements in AGV systems are lacking. Therefore, an attempt was made to include articles from adjoining fields, such as AVs. Whilst articles regarding requirements for the field were identified, they were not plentiful. A significant quantity of the articles discusses for example "usability" from a quality perspective, rather than a requirements engineering perspective. For this reason, the results for each code will be discussed below, taking into account the generalizability of the findings toward AGV systems.

The first identified code is *Safety*. There are articles from the field of AVs and AGVs. The relevant findings from the former are that safety is critical for such systems and that the market will not grow unless the technology satisfies this need. This is a finding that ought to be generalizable across fields to some extent, even if the safety aspect probably is more important for AVs than AGVs. The articles identified in the latter ascertain that AGV systems are to be deemed as safety-critical. Furthermore, they establish the utilization of standards such as ISO 3691-4:2020 as a basis for deriving safety requirements.

The second identified code is *Robustness*. One relevant finding from the subcode *Robustness (AGV)* is the lack of robustness in current AGV systems. This is due to the centralized nature of the system, which has the limitations of not being very proactive in avoiding unforeseen operating conditions. The findings from the subcode *Robustness (AV)* is not deemed very generalizable. This is due to the fact that the issues for such systems, in terms of robustness, are very different from AGV systems. The focus is on how robustness impacts the safety of the vehicle, rather than the impact it has on some measure of efficiency, which is the focal point for robustness in the context of AGV systems.

The third identified code regards *scalability*. Relevant findings, within the context of AGV systems, suggest that scalability is an issue. The literature suggests that this is due to the fact that the computational effort required increases logarithmically with the number of AGVs in the system.

The fourth identified code is *Usability* where no studies were found in the context of AGVs. The chosen studies have been categorized either as *Usability (AV)* or *Usability (General)*. The latter has a more general focus on usability. The generalizability of the findings for those can be considered as high, as they are not pertaining to any particular type of system, but act more as general guidelines. The findings from *Usability (AV)* suggest that it is appropriate to use the ISO 9241-11 standards to evaluate usability for AV systems. This should be applicable to AGVs as well.

The fifth identified code is *Reliability*. The articles discussing it in the context of AGVs mainly concern maintenance strategies and their impact on system throughput. Articles in the subcode *Reliability (AV)* ascertain that this factor has a large impact on the trust and adaptation of the technology. Whilst this might be true to some extent in the case of AGVs, reliability is once again discussed as a factor in system safety. This is important for AGVs as well, but most likely to an even higher extent for an AV system.

The sixth code pertains to articles regarding *Security*. The articles from the subcode *Security AV* recommended following the ISO 26262 standard to mitigate security vulnerabilities for AV systems. Following standards to mitigate risks is something that can be considered generalizable across fields. Research conducted in the field of AGV systems ascertained the need for security as a necessity in order to achieve a safe system.

The seventh and final code pertains to articles regarding *Efficiency*. Research conducted in the field of AGVs considers this to be an issue, as the computational effort for running these systems is high, increasing with layout and fleet size.

5.2 Interview study

The results of the interviews were analyzed using a thematic coding approach, as mentioned in Section 4.2.2. The thematic analysis was performed with the help of two tools, *Atlas.ti* and *Miro*. These tools helped with uncovering themes and codes from the raw interview data. The generative AI from Atlas, which utilizes OpenAI's GPT model to generate codes, was used on the data first. This resulted in a set of quotes and codes. These codes were not utilized for the final coding. The reason for this was that the codes were deemed too narrow by the researchers. However, it served to get some initial ideas regarding what codes could be used. Instead, the thematic coding process was continued by a manual read-through of the transcripts. Themes started to emerge, which were stored on a board in the Miro tool. The data was grouped per interview and each code labeled with a different color. The

results are presented below in Figure 5.1.



Figure 5.1: Overview of the thematic coding board from Miro

In order to make some sense of the data, the thematic analysis was complemented with an affinity diagram, which allows for themes and codes to be visually structured and hierarchically organized. The affinity diagram was also created through the use of Miro. Figure 5.2 below shows the result of this process.

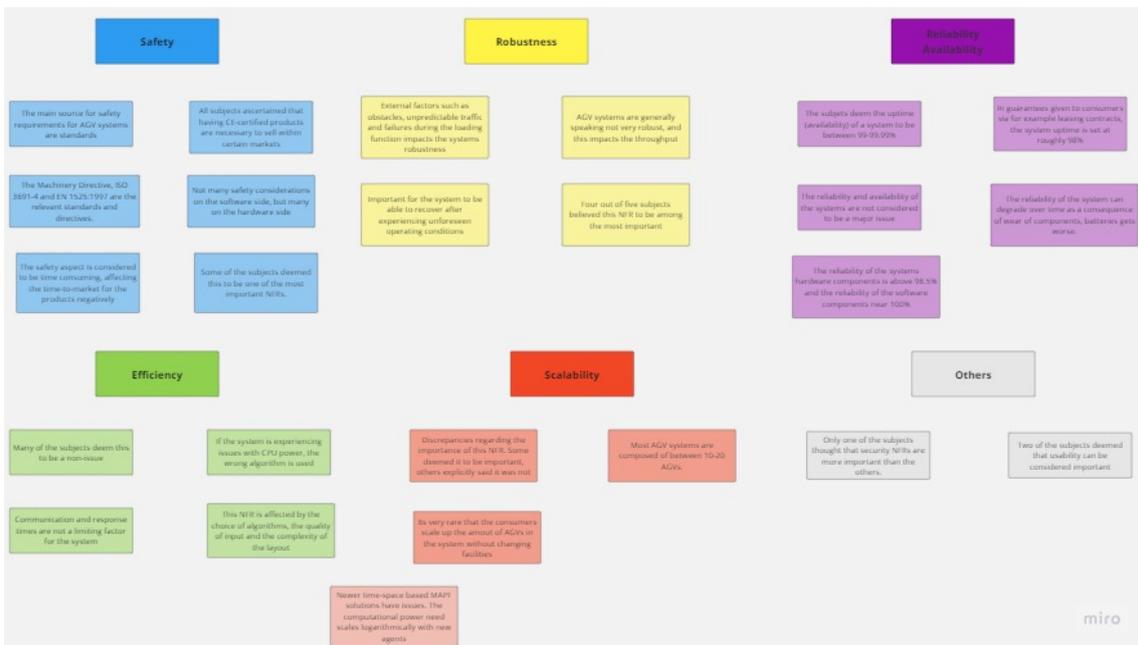


Figure 5.2: Visualization of the affinity diagram. Link

Safety was the first emerging theme. During the course of the interviews, subjects were asked to give their opinion regarding this NFR. This was generally perceived as an important attribute. Several of the subjects explicitly named this as one of the most important NFRs.

"Having CE-marked products is a prerequisite to selling products within certain markets" (E)

"All of our solutions follow the required standards ... The current solutions are safe for humans, which is a part of the CE-certification. This is very important for us" (B)

"Of the NFRs you've mentioned, I deem safety, robustness against unexpected situations, and availability to be amongst the most important" (E)

"There are several considerations on the hardware level ... There are standards that companies are enforced to comply with, for example, the Machinery Directive and the adjoining ISO and EN standards" (A)

"I consider that scalability, as the number of agents, robustness, and safety is the most important factors" (D)

The second emerging theme was *robustness*. This was the NFR that was considered the most important by the largest amount of subjects. Why this is can be summarized with a quote from subject C, *"The overall goal of an AGV system is to execute all orders as fast as possible given the set of resources that you got"*. Many of the subjects deemed that issues regarding the robustness of the systems were the single factor that impacted this the most. This is due to factors such as obstacles, unpredicted traffic, and failures during the loading function which causes delays.

"The hardware itself is very robust. However, the system's robustness is impacted by three types of factors. Firstly, different types of obstacles in the vehicle path. Secondly, unpredicted traffic. Thirdly, failure during the loading function" (C)

"I believe it's very rare for this type of system to be robust. Ive only seen a few systems that could be considered robust and this takes constant surveillance because situations occur and multiply. Ive seen systems that can only handle a few hours without surveillance without something going wrong" (B)

"Its the issues regarding solving the problem with the robustness that is important" (C)

"AGV systems are not very tolerant of external factors such as humans, goods that are placed incorrectly on the pallets and so forth" (E)

The third emerging theme was reliability and availability. Most of the subjects believed that the availability of an AGV system should be between 98.5 and 99.99%. Only one of the subjects mentioned this as one of the more important NFRs.

"The reliability for a single AGV should be above 99%. There should also be zero downtime as a result of deadlocks and issues with software" (A)

"On a single-AGV level, it should be available when it's needed. The overall availability is impacted by scheduled maintenance, service, and so on. An adequate level is above 99%." (E)

"98-99% uptime, considering subsystem breakdowns and systematic errors is to be considered adequate." (D)

The fourth emerging theme was *scalability*. There were some discrepancies regarding the importance of this NFR. Two of the subjects named this amongst the most important, whilst two of the others completely wrote it off.

"Scalability is not as important as some might consider. Most have roughly the same performance in systems that dont exceed 20 AGVs. Its not very often that customers decide to scale up the system without changing/expanding the production facility. The times that this happens its often negligible" (A)

"I only remember one project where this turned out to be an issue, which we later solved. I have helped deliver systems with more than 50 AGVs. This is however not very common. I dont see scalability as a big issue" (E)

"The solutions using MAPF dont have as many rules as say Djiktras. In these old systems, everything was hardcoded and CPU power wasnt a problem. For the MAPF however, a lot of CPU power is needed. It increases almost logarithmically with the number of AGVs in the system. This can become a bottleneck for systems with around 20-25

agents or even as low as 10" (B)

The fifth emerging theme was *efficiency*. None of the subjects deemed this to be amongst the more important NFRs, whilst one of them completely wrote it off. However, there was close to consensus regarding the factors that impacted this particular NFR. The algorithmic complexity, the complexity of the layout, and the quality of the input data. Neither of the subjects believed that communication has a large impact on the system.

"I dont believe that computational efficiency is interesting in this regard. Its the issues regarding solving the problem with robustness that is important. If you have issues with computational efficiency, you are using bad algorithms to solve the problem " (C)

"The communication isnt that limiting. It's enough, depending on the speed of the vehicle, to have a reactivity time of roughly 1 second" (C)

The sixth and final emerging theme was *others*. This regards issues with usability and security, the final two NFRs considered in the study. Only (B) considered security to be important, but still considered that scalability and robustness are more important. (A) and (C) considered that usability could be considered as important as some of the other NFRs. (A) even considered it to be the most important.

5.3 RQ1: Essential requirements

The findings from the literature review give little indication as to what NFRs are to be considered the most important, as they are often discussed in isolation. On the other hand, the results from the interview study ascertain that NFRs regarding *safety* and *robustness* are the most important. An argument could have been made to include requirements regarding *scalability* as well, which also was mentioned as an issue in the literature. The number of subjects that thought they are of the highest importance is the same as for safety. However, two of the subjects also explicitly stated that scalability shouldn't be an issue at all. On top of that, all subjects implicitly stated the importance of safety requirements by ascertaining that a product without a CE-certificate can't be sold in major markets. Furthermore, the literature suggests that the systems are safety-critical. Robustness on the other hand was explicitly stated as the most important NFR type by a majority of the subjects and should therefore be included. The issue is furthermore discussed in the literature, for example, the lack of robustness for deadlock-avoidance algorithms in centralized systems.

All of the elicited requirements were discussed with subject E in order to ascertain their correctness. The first set of requirements are stated in the language

format. This means having a field explaining the ambition, scale, meter and a set of thresholds (must, plan, wish). The "ambition" states the purpose or objective of the requirement. The "scale" defines the unit of measurement and "meter" how to make those measurements. The "must" threshold establishes a minimally acceptable result. The "plan" threshold defines the expected result. The "wish" threshold establishes a better than expected result. For the safety requirements another format as chosen. The "description" is a description of what the requirement should do. The "purpose" is the reasoning of why it is to be implemented. The "trigger" refers to when the requirement occurs. The "pre-condition" refers to a set of conditions that needs to be satisfied before the requirement can be triggered. The "frequency" specifies how often the situation occurs in which the requirement is triggered.

The first stipulated requirement is **RO1**. This requirement emulates the issue ascertained by subject (C) regarding the loading function. In practice, this is a situation that occurs when an agent attempts to load a pallet from a rack and fails due to the sensors identifying for example a faulty pallet or detecting plastic hanging down from the packaging. This causes a fault that is non-recoverable and has to be handled manually by an operator. The rate at which this occurs could not be ascertained by the interviews or the literature study at a precise rate. However, as ascertained by (B) this is something that occurs quite frequently and can be calculated in percentages rather than per mille occurrences.

Tag: RO1	Robustness.LoadingFunction.Failures
Ambition	Limit the downtime of the system by reducing the amount of non-recoverable failures due to failures during the loading function
Scale	Percentage of locations blocked
Meter	N/A
Must	7%
Plan	5%
Wish	3%

Table 5.2: Planguage table for frequency of loading failures

The second requirement, **RO2** is also related to issues during the loading function. As mentioned in the paragraph above, this is a non-recoverable fault that has to be manually handled by an operator. The time this takes is highly dependent on the environment (size of the layout, congestion) and the number of operators that are available.

The third requirement, **RO3** is regarding issues mentioned by all of the subjects. Namely, obstacles blocking the path of the agent. This can be in the form of misplaced pallets, humans interacting with the system, and so forth. The issue is

Tag: RO2	Robustness.LoadingFunction.ResponseTime
Ambition	Fast manual recovery from failure during loading function to limit system downtime
Scale	Seconds from agent failing in loading function to manual recovery by operator
Meter	N/A
Must	60s
Plan	45s
Wish	30s

Table 5.3: Planguage table for recovery time after loading failures

touched upon in the literature, which mentions the lack of robustness for deadlock- and collision-avoidance algorithms. They don't work proactively but rely on the sensors of the AGV. This is a recoverable fault. The occurrence of such faults is once more highly dependent on the context. As mentioned by (B), this fault might be negligible in completely isolated systems. However, these are not representative of the industry as a whole. The factor increases with the number of humans interacting with the system.

Tag: RO3	Robustness.Obstacles.Frequency
Ambition	Limit the downtime of the system by reducing the amount of recoverable failures due to obstacles in the vehicle path
Scale	Percentage of tiles blocked in the layout
Meter	N/A
Must	7%
Plan	5%
Wish	3%

Table 5.4: Planguage table for frequency of obstacles in vehicle path

The fourth requirement **RO4** stipulates the recovery time after an object has been in the vehicle path. The ISO 3691:4 standard stipulates that the AGV is allowed to resume (at the earliest) two seconds after the object is removed from the sensor range.

The safety requirements stipulated will attempt to emulate the ISO 3691-4:2020 standard, as this represents the state-of-the-art safety regulations according to the literature. The use of such standards to identify requirements and conduct research

Tag: RO4	Robustness.Obstacles.ResponseTime
Ambition	Fast automated recovery after vehicle detects an obstacle in its path
Scale	Seconds from agent detecting obstacle to automated recovery
Meter	N/A
Must	15s
Plan	10s
Wish	5s

Table 5.5: Planguage table for manual recovery after obstacle in vehicle path

in the field of requirements engineering has been documented. Furthermore, all of the subjects mentioned the importance of standards within the industry. The requirements will not be stipulated in the form of planguage as this would defeat the purpose of analyzing their impact on the throughput. For example, a valid safety planguage requirement for collisions could look like Table 5.6 below.

Tag: Example	Safety.Obstacles.Collisions
Ambition	A safe system with few occurrences of collisions between an agent and an object
Scale	Amount of collisions divided by amount of collisions avoided
Meter	N/A
Must	10^{-7}
Plan	10^{-9}
Wish	10^{-12}

Table 5.6: Example of planguage requirement for safety

The example provided in Table 5.6 poses two different issues. Firstly, the purpose of the study is to examine the impact on throughput. This requirement would measure how safe the system is. Furthermore, if this type of requirement would have been included, the impact it would have on the throughput of the system is infinitesimal. This is due to very small likelihood of collision occurring. Furthermore, if it occurs it doesn't necessarily entail a lengthy stop. A collision would be defined as any contact being made by the vehicle whilst it is in motion. For example, the vehicle could make contact with a pallet at very low speed. This would force a manual restart, which would not take very long. This combined with the low probability of such a collision entails that the impact that this would have on system throughput is almost

negligible. Secondly, the algorithm used within the system is collision-free. In order to introduce collisions into the system, you would have to hard code parameters. Their impact would be directly proportional to the values chosen. Because of these reasons, the safety requirements will be stated as constraints to the system rather than in planguage. The particulars of this type of requirements were explained in the second paragraph in this section.

The first safety requirement, **SAF1** concerns the speed control of the agent, in other words, what speed is allowed within certain distances to objects. The ISO 3691:4 standard is specific in this case and the distances and velocities can be found in table 2.3. The second and third safety requirements, **SAF2**, **SAF3** are alternations of **SAF1**. **SAF2** will emulate a system with stricter speed control, where the distances to the objects are increased to three tiles. **SAF3** will emulate a system with less strict speed control, where the distances are lowered to one tile.

Tag: SAF1	Safety.SpeedControl1
Description	The system shall adhere to the limitations of speed control as stipulated in Table 2.3. The distance is set to two tiles in the simulation environment
Purpose	Compliance with Machinery Directive allowing for safe operation of the agent.
Trigger	Agent within specified distance to object(s)
Pre-condition	Agent is in automatic mode with functioning personal detection means
Frequency	Any time agent identifies object(s) within the defined distances

Table 5.7: Requirement regarding speed control for agent. Distance to object(s) is 2 tiles

Tag: SAF1	Safety.SpeedControl2
Description	The system shall adhere to the limitations of speed control as stipulated in Table 2.3. The distance to an object is set to three tiles in the simulation environment
Purpose	Operation of agents with a larger marginal to the closest object(s) allowing for a safer system.
Trigger	Agent within specified distance to object(s)
Pre-condition	Agent is in automatic mode with functioning personal detection means
Frequency	Any time agent identifies object(s) within the defined distances

Table 5.8: Requirement regarding speed control for agent. Distance to object(s) is 3 tiles

Tag: SAF1	Safety.SpeedControl3
Description	The system shall adhere to the limitations of speed control as stipulated in Table 2.3. The distance to an object is set to one tile in the simulation environment
Purpose	Operation of agents with a smaller marginal to the closest object making a trade-off between efficiency and safety.
Trigger	Agent within specified distance to object(s)
Pre-condition	Agent is in automatic mode with functioning personal detection means
Frequency	Any time agent identifies object(s) within the defined distances

Table 5.9: Requirement regarding speed control for agent. Distance to object(s) is 1 tile

The next set of requirements (**SAF4**, **SAF5** and **SAF6**) will concern the rated speed of the agents. The rated speed is the travel speed as defined by the manufacturer according to ISO 3691-4:2020. This is of course something that varies depending on the application and context in which the agents are used. Available solutions from Toyota have a rated speed ranging between 2 - 2.2 m/s. **SAF4** will emulate such a solution, with a rated speed of 2 m/s. **SAF5** and **SAF6** will represent solutions with a lower and higher rated speed respectively.

Tag: SAF4	Safety.RatedSpeed1
Description	The system shall have a maximum velocity of 2 m/s
Purpose	Establish max speed for agent to ensure safe operation.
Trigger	Agent within specified distance to object(s) allowing maximum rated speed.
Pre-condition	Agent is in automatic mode with functioning personal detection means.
Frequency	Any time agent is within a permissible distance to an object allowing max rated speed according to SAF1 , SAF2 or SAF3 .

Table 5.10: Requirement regarding the rated speed for an agent. The rated speed is set at 2 m/s

Tag: SAF5	Safety.RatedSpeed2
Description	The system shall have a maximum velocity of 1.5 m/s
Purpose	Establish max speed for agent to ensure safe operation.
Trigger	Agent within specified distance to object(s) allowing maximum rated speed.
Pre-condition	Agent is in automatic mode with functioning personal detection means.
Frequency	Any time agent is within a permissible distance to an object allowing max rated speed according to SAF1 , SAF2 or SAF3 .

Table 5.11: Requirement regarding the rated speed for an agent. The rated speed is set at 1 m/s

Tag: SAF6	Safety.RatedSpeed3
Description	The system shall have a maximum velocity of 2.5 m/s
Purpose	Establish max speed for agent to ensure safe operation.
Trigger	Agent within specified distance to object(s) allowing maximum rated speed.
Pre-condition	Agent is in automatic mode with functioning personal detection means.
Frequency	Any time agent is within a permissible distance to an object allowing max rated speed according to SAF1 , SAF2 or SAF3 .

Table 5.12: Requirement regarding the rated speed for an agent. The rated speed is set at 3 m/s

5.4 Results from the simulations

In this section we provide the results from our computer simulation, answering **RQ2** and **RQ3**. Tables 5.13 and 5.14 represent the two layouts and show the different simulation cases and their respective parameters, the total throughput, and their respective deviation from the base case. The throughput is the median value obtained after five iterations. The low number of iterations is due to the complexity of the simulations. One iteration of each simulation case took roughly five minutes (depending on the layout size and amount of AGVs). Figure 5.3 and Figure 5.4 visualize the throughput deviation from the base case for each simulation configuration in a histogram.

5.4.1 Layout 1: 150m x 150m

Table 5.13 summarizes the results for the larger layout (150m x 150m) given five iterations of the simulation for each case. The values for the throughput is the median of these five iterations. For **SAF4-6** we can see that the throughput decreases significantly (-17) when lowering the rated speed. Increasing the rated speed had a positive effect, albeit not as large (+11). Interestingly, both lowering and increasing the amount of AGVs in the system decreased the output (-8 and -1 respectively). Regarding the effects of speed control, **SAF1-3**, lowering the allowed distance had a small positive effect (+2). Increasing the distance on the other hand had a significant negative effect (-16). Achieving the "wish" threshold for problems during the loading function, **RO1**, had a small, positive effect on the throughput (+2). Decreasing it to the "must" level had a small negative effect (-3). Interestingly, increasing the probability (**R02**) had no impact on the throughput. The random stops also had a small impact on the "wish" and "must" levels (2, -2 respectively). The same goes for increasing the probability (**R03**). The "must" level implied a

decrease of -1 whilst the "wish" level implied a increase of 2. In Figure 5.3 below the deviations from the base case for each of the simulations cases are shown.

Simulation	Number of AGVs	Speed (SAF4-6)	Speed Control (SAF1-3)	Loading-function issues (R01)	Probability (R02)	Random stops duration (R03)	Probability (R04)	Total throughput	Deviation from base case
Base case	5	2	2	45	0.05	10	0.05	36	0
#Layout 1: 01	<u>3</u>	2	2	45	0.05	10	0.05	28	-8
#Layout 1: 02	<u>10</u>	2	2	45	0.05	10	0.05	35	-1
#Layout 1: 03	5	<u>1</u>	2	45	0.05	10	0.05	19	-17
#Layout 1: 04	5	<u>3</u>	2	45	0.05	10	0.05	47	11
#Layout 1: 05	5	2	<u>1</u>	45	0.05	10	0.05	38	2
#Layout 1: 06	5	2	<u>4</u>	45	0.05	10	0.05	20	-16
#Layout 1: 07	5	2	2	<u>30</u>	0.05	10	0.05	38	2
#Layout 1: 08	5	2	2	<u>60</u>	0.05	10	0.05	33	-3
#Layout 1: 09	5	2	2	45	<u>0.03</u>	10	0.05	36	0
#Layout 1: 10	5	2	2	45	<u>0.07</u>	10	0.05	36	0
#Layout 1: 11	5	2	2	45	0.05	<u>5</u>	0.05	39	3
#Layout 1: 12	5	2	2	45	0.05	<u>15</u>	0.05	34	-2
#Layout 1: 13	5	2	2	45	0.05	10	<u>0.03</u>	38	2
#Layout 1: 14	5	2	2	45	0.05	10	<u>0.07</u>	35	-1

Table 5.13: Simulation results based on each factor, Layout 1 (150m x 150m)

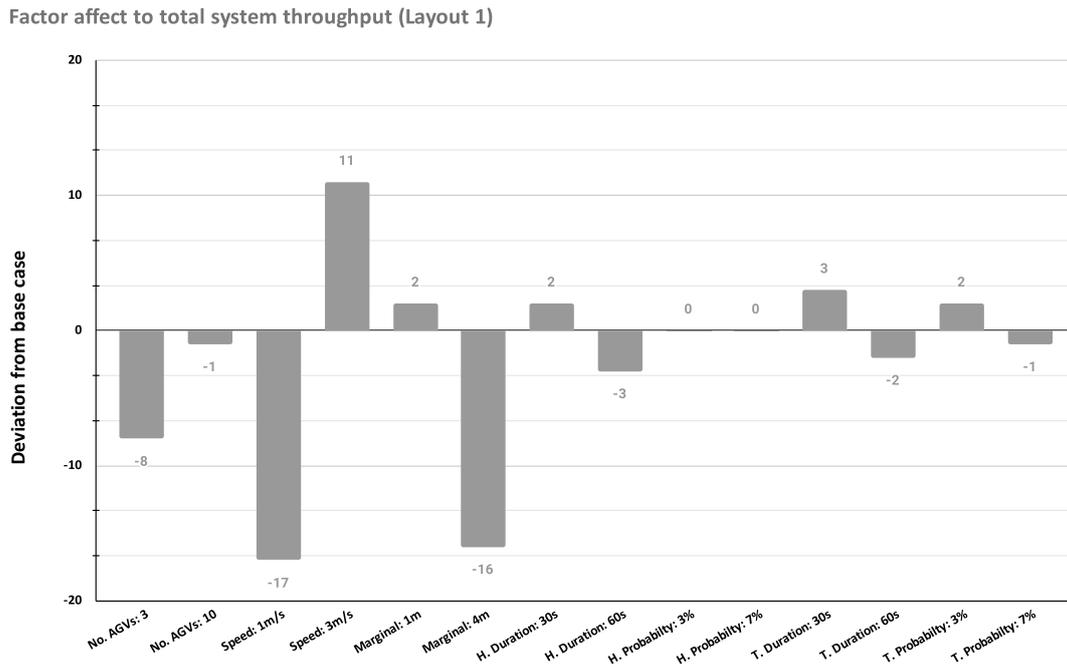


Figure 5.3: Total system throughput deviation from the base case given each parameter (Layout 1 - 150m x 150m).

5.4.2 Layout 2: 75m x 75m

Table 5.14 summarizes the results for the smaller layout (75m x 75m) given five iterations of the simulation for each case. The values for the throughput are the median of these five iterations. When decreasing the amount of AGVs, the throughput decreased of the system deviated -30 from the base case. When increasing the amount of AGVs, the throughput decreased by -3. Regarding the rated speed requirements (**SAF4-6**), decreasing the speed had a substantial effect, lowering the throughput by 50. Increasing the speed had the opposite, but smaller effect (+38). Implementing the speed control requirements (**SAF1-3**) resulted in an increase of 18 and a decrease of 64 when decreasing and increasing the distance respectively. Requirements regarding the loading function (**RO1**) had the effect of increasing the throughput by 2 when the loading time was on the "wish" level. Increasing the time for issues during the loading function to the "must" level resulted in a -3 decrease in throughput. The results for **R02** were unexpected. Both the higher and lower probability resulted in a decrease from the base case (-29, -13 respectively). The duration for random stops (**RO3**) had a positive effect on the "wish" level (+7) and a negative effect on the "must" level (-3). Similar to the results for **R02**, the results for **R04** were unexpected. The increase in probability yielded a decrease of -15, whilst the decreased probability lowered the throughput by -7. Figure 5.4 visualizes the deviations from the base case for each of the simulation cases for layout two.

Simulation	Number of AGVs	Speed (SAF4-6)	Speed control (SAF1-3)	Loading function issues (R01)	Probability (R02)	Random stops duration (R03)	Probability (R04)	Total throughput	Deviation from base case
Base case	5	2	2	45	0.05	10	0.05	103	0
#Layout 2: 01	<u>3</u>	2	2	45	0.05	10	0.05	71	-30
#Layout 2: 02	<u>10</u>	2	2	45	0.05	10	0.05	103	-3
#Layout 2: 03	5	<u>1</u>	2	45	0.05	10	0.05	55	-50
#Layout 2: 04	5	<u>3</u>	2	45	0.05	10	0.05	139	38
#Layout 2: 05	5	2	<u>1</u>	45	0.05	10	0.05	109	9
#Layout 2: 06	5	2	<u>3</u>	45	0.05	10	0.05	36	-64
#Layout 2: 07	5	2	2	<u>30</u>	0.05	10	0.05	103	2
#Layout 2: 08	5	2	2	<u>60</u>	0.05	10	0.05	99	-3
#Layout 2: 09	5	2	2	45	<u>0.03</u>	10	0.05	68	-29
#Layout 2: 10	5	2	2	45	<u>0.07</u>	10	0.05	84	-13
#Layout 2: 11	5	2	2	45	0.05	<u>5</u>	0.05	110	7
#Layout 2: 12	5	2	2	45	0.05	<u>15</u>	0.05	97	-3
#Layout 2: 13	5	2	2	45	0.05	10	<u>0.03</u>	88	-15
#Layout 2: 14	5	2	2	45	0.05	10	<u>0.07</u>	87	-7

Table 5.14: Simulation results based on each factor, Layout 2 (75m x 75m)

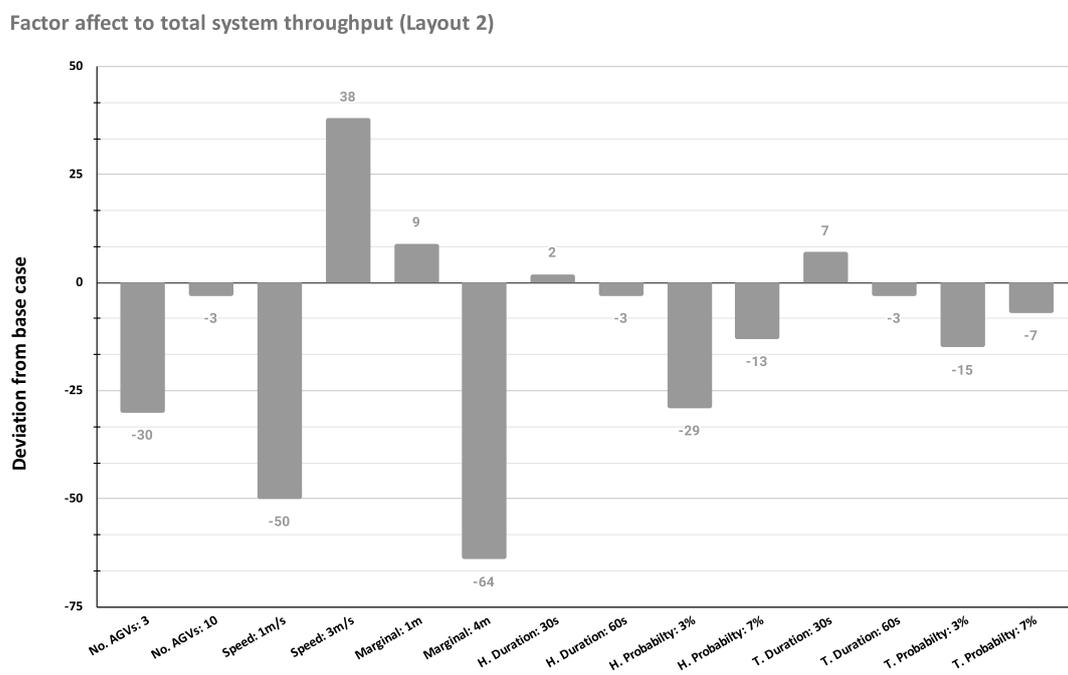


Figure 5.4: Total system throughput deviation from the base case given each parameter (Layout 2 - 75m x 75m).

5.5 Statistical significance

Once the different simulation configurations were simulated, it was decided to verify that the different simulation runs for each configuration were normally distributed. Normal distribution is not a must in this case since there can be some variations between each simulation but the data range should be reasonable.

The Shapiro-Wilks test was utilized to analyze if the simulations were normally distributed or not. The null hypothesis for the test is that the simulation data is normally distributed. The p-value (the threshold for significance level annotated by α) was decided to be 0.05 which is generally considered a conventional threshold. The table below represents the p-value for each simulation configuration and whether or not it exceeded the threshold. A p-value $> \alpha$ indicates a normal distribution while a p-value $< \alpha$ suggests a significant deviation from a normal distribution. As seen in the table below most results were normally distributed but since the sample size is very small (5 simulations/configuration) the results are not definitive and should be interpreted with caution.

Requirement	Layout 1 p-value	Layout 2 p-value
BASE	0.618 $> \alpha$	0.350 $> \alpha$
No. AGVs: 3	0.404 $> \alpha$	0.920 $> \alpha$
No. AGVs: 10	0.657 $> \alpha$	0.287 $> \alpha$
Speed: 1m/s	0.993 $> \alpha$	0.486 $> \alpha$
Speed: 3m/s	1.000 $> \alpha$	0.209 $> \alpha$
Marginal: 1m	0.373 $> \alpha$	0.999 $> \alpha$
Marginal: 4m	0.998 $> \alpha$	0.906 $> \alpha$
H. Duration: 30s	0.965 $> \alpha$	0.519 $> \alpha$
H. Duration: 60s	0.997 $> \alpha$	0.075 $> \alpha$
H. Probability: 3%	0.0187	0.310 $> \alpha$
H. Probability: 7%	0.997 $> \alpha$	0.920 $> \alpha$
T. Duration: 30s	0.047	0.620 $> \alpha$
T. Duration: 60s	0.722 $> \alpha$	1.000 $> \alpha$
T. Probability: 3%	0.959 $> \alpha$	0.820 $> \alpha$
T. Probability: 7%	0.190 $> \alpha$	0.804 $> \alpha$

Table 5.15: Shapiro-Wilk test results per parameter after 5 iterations. ($p > \alpha(0.05)$ -> Assumes normal distribution)

Once the data was deemed to be rational and within the acceptance level there was a need to identify which configurations significantly deviated from the base case. For this, the Paired t-test was utilized which is used to compare the means of two different data sets and identify a statistically significant difference. Here the null hypothesis was declared as not significant and once again a threshold value of 0.05 was used as the α . The results for the paired t-test are visualized in the table below where a p-value $< \alpha$ indicates a statistically significant deviation from the base case.

Requirement	Layout 1 p-value	Layout 2 p-value
No. AGVs: 3	0.051	$0.001 < \alpha$
No. AGVs: 10	0.583	0.198
Speed: 1m/s	$0.001 < \alpha$	$0.000 < \alpha$
Speed: 3m/s	$0.009 < \alpha$	$0.0002 < \alpha$
Marginal: 1m	0.378	$0.037 < \alpha$
Marginal: 3m	$0.005 < \alpha$	$0.000 < \alpha$
H. Duration: 30s	0.436	0.513
H. Duration: 60s	0.833	0.454
H. Probability: 3%	0.454	$0.000 < \alpha$
H. Probability: 7%	0.811	$0.003 < \alpha$
T. Duration: 30s	0.154	0.090
T. Duration: 60s	0.683	0.495
T. Probability: 3%	$0.030 < \alpha$	$0.006 < \alpha$
T. Probability: 7%	0.796	0.199

Table 5.16: Paired t-test results per parameter after 5 iterations. (p $< \alpha(0.05)$ -> Statistically significant)

6

Discussion

In this chapter we will discuss the findings of the study and common threats to validity

6.1 Research question 1

"Identify essential non-functional requirements for AGV systems within a warehouse setting"

Based on the results from the literature review and the interview study, NFRs regarding robustness and safety were to be considered the "essential" requirements. This doesn't mean that the other requirements presented in the thesis aren't important - it serves as a way to get a reasonable scope. Out of the remaining NFRs, reliability/availability wasn't really seen as an issue for AGV systems. Efficiency was not deemed important by any of the subjects, and one of them wrote it off completely. Scalability could have been included since some subjects referred to it as a non-issue, whilst others deemed that it was a problem. Its impact is however studied to some extent with the increase/decrease in the number of AGVs as a case during the simulation. However, what would have been interesting in that case would be to get measurements regarding the computational effort, as this seems to be the most limiting factor rather than throughput. Due to limitations in time during the interviews, there was never a deep-dive into the subjects of security and usability. The subjects were asked after having discussed the other NFRs whether those would be considered more important. This could be seen as somewhat leading, and perhaps the answers would have been different if the questions were framed in some other way.

The combination of a literature review and an interview study was conducted in order to achieve triangulation and avoid mono-method biases. However, the results from the literature review were not very helpful in answering what type of requirements would be used for **RQ1**. This is mostly due to the fact that most of the articles aren't discussing "safety" or "scalability" from a requirements engineering standpoint, but rather a quality perspective. Furthermore, they are most often discussed in isolation, so to gauge which ones are the most important given the articles in the literature review is difficult. They did give insight into how the requirements could look, however, for example using existing standards for safety requirements.

The interview study was very insightful and helped answer **RQ1**. If the researchers were to conduct a similar study again, this would be the focal point of that study. By perhaps doubling the number of interviews and having a few follow-ups regarding specific requirements, the answers for **RQ1** could have been more reliable.

The requirements that were chosen for the study were based both on the answers from the interview study (**RO1-4**) and findings in the literature (**SAF1-6**). For the former, it was a bit difficult to establish the exact properties of such requirements. The question was asked in the latter interviews, and the most straightforward answer was that these types of unexpected operating conditions would be occurring in percentages. It was a difficult question to answer, as it's heavily context-dependent. A system in full isolation might not suffer from these conditions at all, whilst a system that is interacting with humans and manual forklifts might have large issues. For the safety requirements (**SAF1-6**), a choice was made to make them more as constraints to the system. This choice was made due to the fact that a normal planguage NFR would be derived from a set of functional requirements. The planguage requirement would be stipulated in terms of for example the risk of collision. This risk would be very low, say between 10^{-9} and 10^{-12} . The impact that this would have on the throughput is negligible. On the other hand, the system constraint that this NFR is derived from will have an impact on the throughput, and therefore those constraints were chosen to represent safety NFRs instead.

Summary

The types of NFRs that were deemed most important by the domain experts were *robustness* and *safety*. Findings from the literature review and background helped shape the safety requirements (**SAF1 - SAF6**). Findings from the interview study helped shape the robustness requirements (**R01 - R04**).

6.2 Research question 2

"Evaluate the impact of the non-functional requirements found in RQ1 on the system throughput"

This pertains to cases 03-14 in Tables 5.13 and 5.14. Regarding the impact of different distances for speed control (**SAF1 - SAF3**), the results were as expected. An increase in the distance for speed control led to a decrease in the throughput for both layouts. This is rational, as a longer distance for speed control means longer travel paths for the AGVs, and increased queue and waiting times at for example the output stations. On the other end, decreasing the distances means decreased travel path lengths and decreased queue and waiting times, yielding a positive impact on the throughput.

The impact of the rated speed for the vehicles (**SAF4 - SAF6**) were also expected.

Decreasing the rated speed led to a negative impact on system throughput. A reverse, but smaller effect, was identified when the rated speed was increased. This is most likely due to the fact that increasing the speed also increases congestion in the system, which has a negative effect on the throughput.

Regarding the impact of **R01** and **R03** the results were as expected. In both layouts, the deviation from the base case had a negligible effect on the throughput when the time was decreased. One might wonder why the impact of the two was very similar when the loading function errors were considerably longer. This is due to the fact that there are more tiles in the layout where the random stops could occur, relative to the amount of tiles where loading function errors could occur.

The results for **R02** and **R04** were as expected for layout one. They had a slightly positive impact when increased and a slight negative impact when decreased. However, for the smaller layout (75m x 75m) the throughput decreased both when increasing and decreasing the likelihood of loading time errors. The rational result would be for the throughput to increase when the probability decreases, such as it did in the first layout. The results were analyzed and inspected visually to give some idea of why this was the case. The rational conclusion was that the waiting times for the output station were a bottleneck in the smaller layout. When the agents stopped in the middle of an aisle, they were less likely to be in the path of another agent, and they decreased the time spent by the output stations. Thus decreasing the probability of these random failures, led to the agents having to take routes around each other instead of taking the shortest path leading to a negative impact on the total system throughput. This is not something that is to be considered usual for these types of systems. Rather, it is an edge case caused by the particulars in the layout.

To relate back to the literature, a relevant finding was that there is a high desirability to have systems that are capable of coping with unexpected operation conditions. The results that has been obtained through this research further proves this point, and provides an example to what degree different robustness issues that current solutions are experiencing impact the throughput. As the results clearly show that the impact of such issues are negative, it ought to provide incentives for industrial practitioners and researchers to solve these issues. Regarding the safety requirements, it is of course interesting for practitioners to gain insight to how for example standards impact system throughput. However, these standards exist for a reason and sacrificing system safety for increased throughput is not advisable. Instead, the industry should be working towards even more safe systems. Doing so could increase the trust in the technology, leading to further possibilities for sales and investments and a heightened growth rate for the industry as a whole.

Summary

The results for **SAF1 - SAF6** was as expected. Increasing the rated speed, and decreasing the distance for speed control had a positive impact on the throughput, and vice versa. The simulations yielded unexpected results in layout 2 for **R02** and **R04**. It was ascertained that this represents an edge case for the system. The results for **R01** and **R03** were expected. There was a slight increase in throughput when the time for loading function failures and random stops was decreased, and vice versa.

6.3 Research question 3

"Evaluate the impact of the non-functional requirements found in RQ1 on the system throughput given a set of specific, real-world scenarios"

This pertains to the differences between the results found in the two layouts, as well as the increase and decrease in the number of agents in the system (cases 01 and 02).

Regarding the former, decreasing the layout size had the impact of intensifying the results from **RQ2**. This is most likely a result of shorter travel times, which leads to the different requirements having an overall larger effect for each case. Regarding the rated speed **SAF4-6**, the overall impact was similar for both layouts. When the speed was decreased, the percentage loss of throughput was similar (47.2% for the larger and 48.5% for the larger). Similar results were identified for increasing the rated speed, which yielded an increased throughput of 36.8% for the smaller layout and 30.5% for the larger layout. The differences in effect size could be explained by a reduced relative impact on the travel time for the larger system. Increasing the speed does reduce the travel time in the larger system, but the relative impact would be smaller than for a system where the distances between objectives are shorter.

Regarding the speed control requirements (**SAF1-3**) the results were amplified in the smaller system. Decreasing the distance had a relative impact of +5.6% for the larger system and +8.7% for the smaller system. The discrepancies in the relative impact could be explained by the fact that the smaller system is already congested, and there is less empty space for the agents to operate in. The relative impact of increasing the distance for the speed control requirements was -44.4% for the larger layout and -62.1% for the smaller layout. This can be explained with the same reasoning, the smaller system is already more congested.

Concerning the probabilities of loading function errors and random stops (**R02** and **R04**), the relative impact when increasing the probabilities in the larger layout was measured at +2.7% for both NFRs. For the smaller layout, the relative impact of **R02** and **R04** was measured at -28.3% and -14.5% respectively. As mentioned in the previous section, there were discrepancies regarding the results between the

different layouts. This can be explained by system bottlenecks in the second layout. As the travel paths are considerably shortened, the agents will spend more time at the output stations, which becomes the system's bottleneck. When an agent stops inside an aisle due to a random stop or issues during the loading function, they inadvertently impact the system throughput in a positive way as the queue and waiting times for agents at the output stations are lowered.

The relative impacts of **R01** and **R03** (time for loading function errors, random stops) on the different layouts were similar. When decreasing the time for **R01**, the relative impact on the system throughput for the larger layout was 5.6% and 6.7% for the smaller layout. When increasing the time, the relative impact on system throughput was -8.3% for the larger layout and -2.9% for the smaller layout. When the time for **R03** was increased in the larger layout, the relative impact was -8.3% while for the smaller layout, it was measured at -2.9%.

The impact of decreasing the number of agents in the system was as expected. For the larger layout, the relative impact was measured at -22.2%. For the smaller layout, the relative impact was measured at -29.1%. The reason why the relation is not linear (which would entail -40% in throughput for both systems) is most likely due to the decreased congestion in the system. This could also explain why the impact is larger in the smaller layout, where congestion has a bigger impact. When the amount of AGVs was increased, the relative impact for the larger layout was -2.7%. The relative impact for the smaller layout was measured at -2.9%. These results might seem to be unexpected, but there is an explanation. Rationally, one would expect diminishing returns, where the throughput is increased and the efficiency of each agent is decreased due to congestion. However, the system has in this case reached a point where (in both layouts) the output stations are the system bottleneck. Increasing the number of agents in such a system would not increase the amount of tasks it could handle, but only add to the congestion. This would lead to a small decrease in throughput, as can be seen for both layouts.

Summary

The impact that the different NFRs have on the system's throughput is generally amplified in the smaller layout. Decreasing the fleet size leads to a larger, relative decrease in throughput for the smaller layout due to increased congestion compared to the larger layout. Increasing the fleet size have diminishing returns until the system is at max capacity and an increase in agents mostly leads to more congestion, lowering the throughput.

6.4 Generalizable experiences

The set of requirements that was studied is highly specific. In order to generalize our findings beyond this specific context, we will offer advice to researchers aiming to conduct similar research.

The conducted study utilized an extensive background and literature review, as well as an interview study to gain insights regarding the most important NFRs for this type of system. If the researchers were to conduct a similar study again, the interview study and obtaining more participants would be given higher focus in order to answer this question. A focus group for the initial stages, combined with follow-up interviews regarding specific requirements, would have been ideal.

In our case, a simulation tool was created to assess the impact of the NFRs. However, it is not necessary to use a simulation tool to assess the impact of NFRs on AGV systems. It could, for example, be replaced with a mathematical formula to estimate system throughput. Whilst this would abstract away some of the real-world complexities, it would also save a substantial amount of time. This saved time could have been used to gain more in-depth knowledge regarding the specific requirements or conduct more interviews. It would also have mitigated the issue of the complexity of the simulation tool, which led the researchers to use only five iterations for each base case.

Whilst the interview subjects were certain about the type of issues AGV systems face, they were hesitant to provide exact values to determine the frequency of these problems. A time study at an actual warehouse or production facility that uses AGVs could ascertain those values.

6.5 Threats to validity

In this section, we will discuss the impact of different validity threats. Sequentially, we will discuss the conclusion validity, internal validity, construct validity, and external validity of the research.

6.5.1 Conclusion validity

Conclusion validity pertains to the relationship being tested and refers to whether it is reasonable to presume covariation. There are several major threats, for example; low statistical power, random irrelevancies in the experimental setting, and the random heterogeneity of possible respondents. Random irrelevancies refer to noise or extraneous factors that are irrelevant to the research questions but still might impact the results (such as randomness introduced by the simulation in this study). The random heterogeneity of the respondents refers to the natural variation of characteristics among the individuals that partake in the interview study. Tests regarding the statistical significance was discussed in Section 4.3 and the results are shown in Section 5.5.

Worth mentioning regarding the statistical significance tests however, are the fundamental limitations of the tests that have been used. Not all of the values in Table 5.15 are normally distributed. This departure from normality can affect the validity of the results. Whilst t-tests can be used to detect significance for smaller sample

size (five iterations in this case), there is an argument to be made for using a higher p value to detect significance with a smaller sample size. Furthermore, the use of paired t-tests could have impacted the generalizability of the findings, as they pertain specifically to the data being compared.

Regarding random irrelevancies in the experimental setting, this could impact the results for **RQ2** and **RQ3**. However, both of the questions have been answered with the help of a computer simulation. In other words, it takes place in a non-empirical setting, where all the rules are predefined. For that reason, there shouldn't be any statistical noise or extraneous factors to consider. As a result, this factor was deemed to not have impacted the results in any major way.

The random heterogeneity of respondents is a threat to the results obtained from the interview study, which has been used to answer **RQ1**. The results from this section may introduce variability that is not accounted for in the study, and the generalizability of any findings could have been impacted.

6.5.2 Internal validity

Internal validity pertains to the causality between potential relationships in the study and speaks for the validity of the research itself. Common threats to internal validity include; selection bias, history, maturity and testing. Selection bias occurs when participants of a study are not selected randomly. History and maturity refer to external events that occur during the course of a study and changes that occur naturally over time, respectively. Finally, testing refers to effects that occur when participants repeatedly are tested for some response, which might influence their behavior.

Regarding selection bias, the participants of the study were selected based on availability for the interviews. This might have impacted the causality of relationships identified in the interview study and as a result the answers to **RQ1**. However, the respondents were deemed to be representative of the industry as they include a range of individuals with different experience levels and roles within different companies.

Concerning the history and maturity, it refers to external events that occur during the course of a study and changes that occur naturally over time, respectively. Neither is deemed to have an impact on the research at hand.

Testing should not be an issue for any of the research questions. **RQ2** and **RQ3** are answered with a computer simulation and **RQ1** does not involve any repeated interviews or tests with the same subjects.

6.5.3 Construct validity

Construct validity pertains to the transformation of an idea, concept, or behavior into a functioning and operating reality. It refers to whether specific measurements are model-independent and dependent on variables by which the hypothesized theory is constructed. Common threats include; construct under-representation, irrelevant variance in the construct, mono-operation bias, and mono-method bias. Construct under-representation occurs when the model doesn't adequately represent the reality it is trying to emulate. As a result, measurements attained from said model might be erroneous. Mono-operation bias occurs when only a single measure or operationalization is used to represent reality. Mono-method bias occurs when only one method is used to collect the data for the model.

The simulation model used to answer **RQ2** and **RQ3** will in part be suffering from construct under-representation, as many of the complexities of a real-world warehouse environment has to be abstracted away in the model. Irrelevant variances in the construct are less of a problem for the model. This is due to the fact that the variables will be controlled and pre-programmed and their values will not be influenced by external factors. However, the variance may still occur due to the fact that the simulation is affected by for example the processing speed of the computer and also the fact that each simulation has some randomness to it.

Mono-operation bias could affect the results for **RQ2** and **RQ3**. This is due to the fact that the model might fail to capture the complexities of a real-world warehouse setting.

The researchers tried to mitigate any mono-method bias by collecting data to answer **RQ1** using a combined literature and interview study. However, finding an answer to this question in the literature was difficult. The results heavily relied on the interview study as a result - which might induce bias. This bias could have been propagated, as the results from **RQ1** were used to simulate the results for **RQ2** and **RQ3**.

6.5.4 External validity

External validity pertains to the generalization of relationships across settings, actors, and time. In other words, external validity is concerned with the extent to which the results of a study are relevant and applicable in the real world. The choice of settings and actors might impact the generalizability. Furthermore, the lack of a representative sample and the choice of methodology can impact the generalizability of any results.

The study's ability to be generalized is limited. This means that the findings of the study may not be applicable or relevant to other populations, settings, or conditions beyond the specific sample or context in which the study was conducted. This limitation is acknowledged in the literature, which suggests that computer simulations

are inherently limited in their ability to be generalized. This is because computer simulations aim to model specific types of real-world systems, which may not accurately represent all possible scenarios or conditions. As a result, the findings for **RQ2** and **RQ3** in the study may be affected by this limitation. It is important to note, however, that the limitations of generalizability do not necessarily detract from the value or importance of the study's findings within the specific context in which it was conducted. Moreover, the generalization of findings is not the goal of all studies. In this case, the aim is to gain an understanding of the subject rather than generalize it across actors, contexts, and time.

The lack of a representative sample might have impacted the study results. As mentioned previously, the utilized sampling method for the interview study was convenience sampling which as mentioned earlier might have impacted the generalizability of the results for **RQ1**.

7

Conclusion

The purpose of this study was to evaluate the impact that essential NFRs have on system throughput and how it is impacted by the choice of layout and fleet size. This was achieved by a mixed-methodology approach. The essential requirements were identified with the help of an interview study and a literature review. The impact that these requirements had on system throughput was then simulated using a tool developed during the study.

The simulation tool was developed with the goal of emulating AGVs in a warehouse environment. It utilizes a variation of the A^* algorithm, based on both time and space. Two different layouts were created for the simulation, representing different warehouse environments. A smaller layout (75m x 75m) and a larger layout (150m x 150m).

The interview study ascertained that requirements regarding *safety* and *robustness* were to be considered the most important. Findings from the literature review and background helped shape a set of safety requirements regarding speed control and velocity. Findings from the interview study helped shape four robustness requirements regarding loading function issues and random stops along with their respective probabilities.

The requirements were used as input to the simulation model, allowing for benchmarking of the system throughput. For each layout, each of the requirements (and thresholds) was varied independently and compared to a base case. The results ascertain that the effect that the NFRs have on system throughput is profound. The researchers established that the impact of the different NFRs generally are amplified in the smaller layout. Decreasing the fleet size leads to a larger, relative decrease in throughput for the smaller layout due to increased congestion. Increasing the fleet size has diminishing returns until the system is at max capacity and the increase in agents only leads to more congestion, lowering the throughput.

The thesis was conducted in collaboration with Consat AB as an industrial partner. Consat delivers services in various fields, such as industrial technologies, IT and automation. The goal of the thesis is to assess the impact that NFRs have on AGV systems and give Consat further insights on the subject. The study also aims to contribute to global research in the fields of automation and requirements engineering.

7.1 Future work

This study has shown the impact that a certain set of NFRs regarding *robustness* and *safety* has on the system throughput, and how it varies based on differentiating layouts and fleet size. Future work could continue to study the impact of similar requirements on more advanced simulation tools. The set of NFRs chosen for the research is by no means exhaustive, and work could continue on the same line as the research conducted.

Due to the limitations in the scope of the research, NFRs regarding *reliability*, *availability*, *scalability*, *security* and *usability* was omitted. It could be interesting for future work to encompass such requirements for example the impact that reliability and availability have on the system throughput. It would also be interesting to see the impact that scalability has on for example the computational complexity and effort for AGV systems. To expand upon the usability, future research could encompass what impact the flexibility and adaptability of the system have on its efficiency. Research regarding how usability requirements can impact operator training and retention would also be of interest.

For this research, the A^* algorithm was used as the path-finding algorithm to direct the agents during the simulation. It would be interesting to see the impact of different NFRs given other kinds of pathfinding algorithms, utilizing, for example, D^*Lite algorithm, the ant colony optimization algorithm, or the genetic algorithm.

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Interview Guide

Interview questions

Individual experience

- Can you give us a short introduction regarding your experience in the context of AGV systems.

Safety

- What do you believe impacts the safety of an AGV system?
- Which if any safety regulations does your AGV solutions comply to?
 - How does these regulations impact the requirements of said solutions?

Robustness

- What do you believe impacts the robustness of an AGV system?
- When is an AGV system considered robust?

Scalability

- What impacts the scalability of an AGV system?
- When is a system deemed scalable?

Efficiency

- What impacts the computational efficiency of a centralized AGV system (in the context of path-finding)?
- What sets the upper limit for computational time?

Reliability/Availability - Stipulates how long the system can run before experiencing a failure.

- What do you believe impacts the reliability of an AGV system?
- What would you see as an appropriate threshold for the reliability of a centralized AGV system?

Ending:

- Would you consider other non-functional requirements, such as Usability or Security to be more important than the types that we have discussed?
- We have discussed a number different non-functional requirements. Which ones do you identify as the most essential?
- Is there anything you believe we have missed that you would like to add?