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A State of the Art Map of the AGVS Technology and a Guideline for How and Where to Use It

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Mark Schiller Luttenberger and Camilla Feledy

ABSTRACT

The Automated Guided Vehicle (AGV) was invented in 1953 and is a driverless transport vehicle used for horizontal movement. AGVs are battery powered, centrally computer-controlled and often used in industrial environments like production sites or warehouses. When multiple AGVs cooperate it is called an Automated Guided Vehicle System (AGVS).

Scania is looking into implementing AGVSs but first wants a thorough understanding of the technology and how it can be used. The purpose of this master thesis is therefore to map the technology connected to AGVSs and create a guideline for how and when to use it. This is done by conducting a thorough literature study in combination with information gathering from interviews with suppliers as well as current users of the technology. With this method a complete and reliable state of the art map of the technology can be created.

To create a comprehensive map of the technology the following areas have been covered; AGV types, the AGV guidance control system, navigation methods, obstacle avoidance, safety, batteries, charging, environmental aspects, operational aspects and the future.

There are a great number of AGV types and technological alternatives connected to AGVSs. The recommendation to Scania is to start implementing one or several Forklift AGVs. This is the most common AGV type, it handles pallets which is a standardised load carrier and it is a natural change from the current manual forklifts. They should navigate with the help of artificial laser navigation as this is a flexible and well tested technology. The implemented AGVS should not use obstacle avoidance because of its lack of added value in an industrial environment. Regarding safety it is recommended that Scania chooses the safety equipment recommended by the supplier chosen. It is however also important that they do their own risk assessment to investigate the risks connected to AGVs in their specific environments. When it comes to energy, the battery should be chosen based on the charging scheme and the choice of charging scheme should be based on the qualities and the characteristics of the operations the AGV is to conduct.

Besides the technological aspects it is important to consider the environmental aspects that can affect an AGVS. The major environmental aspects to consider is the condition of the floor, interference with pedestrians and manual forklifts and the WLAN connection.

The final area covered in the report is the operational aspects. These are the factors that are decisive when analysing a process' suitability for an AGVS and are identified to help Scania determine which of their material handling processes that are most suitable for an AGVS implementation. The factors that indicate that an AGVS implementation can be appropriate are; if a process can be clearly defined, if all tasks within a process can be automated, if pedestrians and manual forklifts will not interfere with the AGVs operation, if the floors are in a condition that is suitable for an AGVS, if the load can be handled automatically, if the load carriers are standardised and if the implementation of an AGVS will cut costs.

SAMMANFATTNING

AGVn (Automated Guided Vehicle) uppfanns 1953 och är ett förarlöst transportfordon för horisontell förflyttning. AGVn är batteridriven och styrd av en centraldator. Den används ofta i industriella miljöer såsom inom produktion eller i lager. När flera AGVer används tillsammans bildar de ett Automated Guided Vehicle System (AGVS).

Scanias mål är att implementera AGVS men först vill man få en grundlig förståelse för tekniken och hur den ska användas. Syftet med detta examensarbete är därför att kartlägga tekniken och skapa riktlinjer för hur och var den ska användas. Detta görs genom en grundlig litteraturstudie i kombination med intervjuer med leverantörer och användare av tekniken. På det viset kan en fullständig och tillförlitlig kartläggning av tekniken skapas.

För att ge en heltäckande beskrivning av tekniken har följande områden behandlats i studien; AGV-typer, AGV guidance control systemet, navigationsmetoder, undvikande av hinder, säkerhet, batterier, laddning, omgivningsfaktorer, operationella faktorer samt framtiden för tekniken.

Det finns många olika typer av AGVer, liksom olika alternativa tekniska lösningar för AGVS. Scania rekommenderas att börja med att implementera gaffeltruckAGVer. Det är den vanligaste typen av AGV, den hanterar pallar vilket är en standardiserad lastbärare och är en naturlig utveckling av dagens gaffeltruckar. AGVerna bör användas med artificiell lasernavigering som navigationsmetod då det är en flexibel och välbeprövad metod. AGVerna borde inte konstrueras för att undvika hinder då det inte tillför något extra värde i en industriell miljö. Angående säkerhet borde Scania använda sig av den utrustning som rekommenderas av leverantören. Scania borde dock alltid utföra sin egen riskanalys för systemen och omgivningarna de kommer att befinna sig i. Beträffande drift bör man välja batteri beroende laddningsmetoden som i sin tur ska väljas beroende på användningsområdet för AGVerna.

Utöver de tekniska aspekterna är det viktigt att beakta omgivningsspecifika faktorer vid valet av ett AGVS. De viktigaste faktorerna här är kvaliteten på golvet, samspelet av människor och manuella gaffeltruckar med AGVerna samt kvalitén på WLAN-uppkopplingen.

Den sista delen som behandlas i rapporten är de operationella faktorerna. Dessa faktorer är avgörande när en process ska utvärderas för att bestämma huruvida det är lämpligt med ett AGVS eller inte. Dessa ska hjälpa Scania att identifiera i vilka processer de ska implementera AGVS. De faktorer som indikerar ifall det är lämpligt att implementera ett AGVS är: kan processen tydligt definieras, kan alla stegen i processen automatiseras, är det en process som är isolerad från människor och manuella gaffeltruckar, är lastbärarna standardiserade och kommer en implementering av ett AGVS faktiskt att leda till sänkta kostnader.

TABLE OF CONTENT

1 INTRODUCTION

This chapter describes the background of the master thesis and the company where it is executed. The problem is then described together with the research purpose. Finally the focus, delimitations and the target group of the report are specified and the structure of the report outlined.

1.1 BACKGROUND

The Automated Guided Vehicle (AGV) was invented in 1953. The idea came from an American inventor that had the thought of replacing the driver of a tractor-trailer for transporting goods. Savant Automation[1] implemented the invention and the first Automated Guided Vehicle System (AGVS) was installed as a tractor-trailer in 1954 at Mercury Motor Freight Company in Columbia, South Carolina, for long-distance round-trip shipping operations in the factory, see figure 1.1 (Ullrich, 2015 p.2).

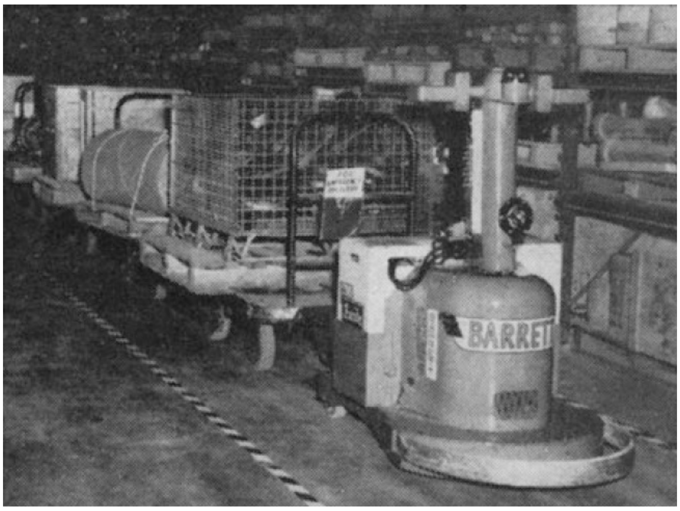

Figure 1.1 - One of the first American AGVS, built starting in 1954, working as a tractor for five trailers (Source Barrett-Cravens/Savant Automation (1958) according to Ullrich (2015, p.2))

At this time the AGVs had mechanical safety bumpers and were guided by a simple wire (active inductive guidance) in the floor or an optical sensor (Ullrich, 2015 p.2-3). During the years to come a great market demand, primarily from the automotive industry, drove the development of more advanced technology in a rapid pace (Ullrich, 2015 p.7). AGVs came with many advantages that were sought-after by the industry. They provided cost savings, increased efficiency, reduced the damage to transported materials (Mertz, 1981, cited in Martínez-Barberá and Herrero-Pérez, 2010b, p.459), increased flexibility, increased space utilization and increased level of safety (Ganesharajah, Hall and Sriskandarajah, 1998).

At the end of the 80's the industry was hit by a severe recession. The AGVs were expensive and did not contribute with the flexibility that was promised. At about the same time Lean Production was introduced. The philosophy originated from the Japanese automobile manufacturing industry, increasing quality and lowering manufacturing costs. Focus now shifted from the inflexible AGVs to this new method as money needed to be saved, not spent on expensive technology. At the end of the 90's new advances in technology enabled a new era of AGVSs that were more flexible and reliable. Contact-free sensors were developed for AGVs, which made electronic guidance possible.

[1] Savant Automation is an American producer of automated guided vehicles.

Active inductive guidance was no longer the only alternative; instead new technologies such as laser navigation was introduced. It also became possible to control the AGVSs with a standard PC which made the handling of the system easier (Ullrich, 2015 p.8-10).

This new era continues to this day and AGVSs are more popular than ever. This can for example be seen in the number of publications with the phrase "Automated Guided Vehicle" in its title, abstract or keywords from the first digital publications in 1974, and up to now, see figure 1.2. It is obvious that the trend has been increasing during this period, with a temporary decline in the 1980s.

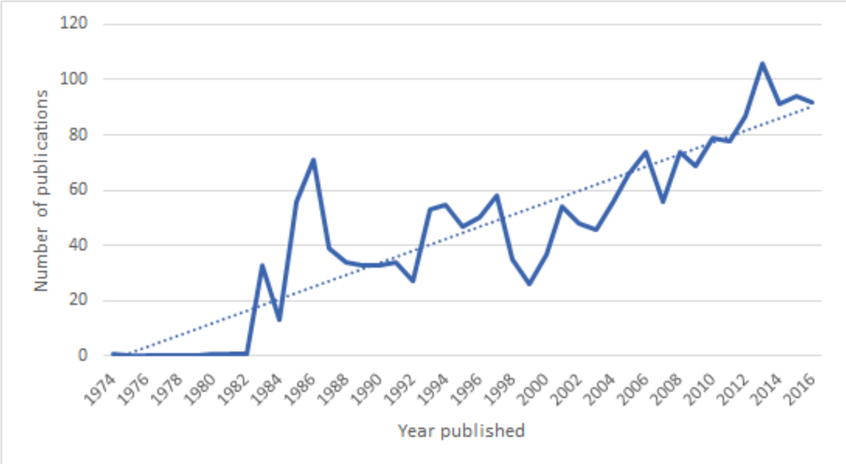

Figure 1.2 - An illustration of the number of publications with the phrase "Automated Guided Vehicle" in its title, abstract or key words. The data used can be found in Appendix A.

In the beginning of the 80's Scania started to implement AGVSs as well. According to Staffan Garås, Senior Advisor for Global Logistics Development at Scania, there was an automation trend in Sweden and Scania therefore started implementing AGVSs with active inductive guidance. These were however phased out in the middle of the 90s as a new trend reached Scania; lean production. Focus shifted from having a lot of material close to the production line to having the needed amount of material close to the line. This increased the importance of having a flexible material handling system, which the AGVS did not provide. Garås (2017) also adds that there were technical issues with the big and complicated AGVSs that led to too many disturbances in Scania's production.

The technology has since developed a great deal and modern AGVSs come with many more advantages than the early ones. Lundgren (2017) has seen that AGVSs are a part of the big trend Industry 4.0 and that many of the German automobile manufacturers are implementing this new technology. The technology is also spreading to new market segments such as retail. In 2012 Amazon, the largest Internet-based retailer in the United States acquired the AGVS producer Kiva Systems and deployed 15 000 AGVs across 10 of its warehouses with the aim to reduce delivery lead times and increase customer service levels (D'Andrea, 2012). This new field of application increases the speed of the technological development even more.

Scania now wants to follow the trend and modernize their production. The reasons for this are partly since they do not want to fall behind this new technology and partly because of Scania's core priorities; safety/environment, quality, delivery and cost. These are, as mentioned above, areas where an AGVS can be very beneficial.

1.2 Company description

Scania is one of the world's leading manufacturers of trucks and buses for heavy transport applications as well as industrial and marine engines. It is a global company with 44 500 employees and had a turnover of 95 billion SEK in 2015. In 2015 they sold 70 000 trucks which is about one truck every 7.5 minutes (Scania, 2016). The sales and service network is represented in more than 100 countries. Research and development are concentrated in Sweden with the company's headquarters in Södertälje and production takes place in Europe and South America (Scania Group, 2017a).

1.2.1 The history of Scania

Founded in 1891 the company has a long history behind it. At this time it was called Vagnfabriksaktiebolaget Södertelge (Vabis) (Scania Group, 2017b). Vabis started by building railway carriages (Ahrén and Bühlmann, 2015) and built their first truck in 1902. Parallel to this, in 1900, Maskinfabriksaktiebolaget Scania was founded in Malmö. Their first product was bicycles but they soon started producing motor vehicles with their first truck shown in 1902. Nine years later, in 1911, Scania and Vabis merged, creating the new company Scania-Vabis (Scania Group, 2017b) as a result of ever-tougher competition (Perta, 2017).

In 1921 Scania-Vabis went bankrupt. A new company was established that took over the old name. It decided to focus its business operations on heavy trucks and buses and cease the production of passenger cars. Up until the Second World War buses were the largest business area, today trucks dominate the company's production. Export took off in the 1950s and Brazil was among the first export countries outside the Nordic region (Perta, 2017).

In 1969 Scania-Vabis merged with Saab and Scania became a division of the Saab-Scania Group. In 1995 the Board of Directors decided to divide the Group into two independent companies, Scania AB and Saab AB. Scania became a wholly owned subsidiary of the company Investor. In 1999 the competitor Volvo made an offer to buy Scania. This was however stopped by the European Union's competition authority in 2000 as they did not approve of the acquisition. The same year Volkswagen became the main shareholder of Scania. In 2006 MAN made an offer to buy Scania but withdrew it early in 2007. A year later, in 2008, Scania became a subsidiary of Volkswagen (Perta, 2017) and in 2014 Scania became a wholly owned subsidiary of the Volkswagen group (Scania Group, 2017d; Perta, 2017). A timeline of Scania's history can be seen in figure 1.3.

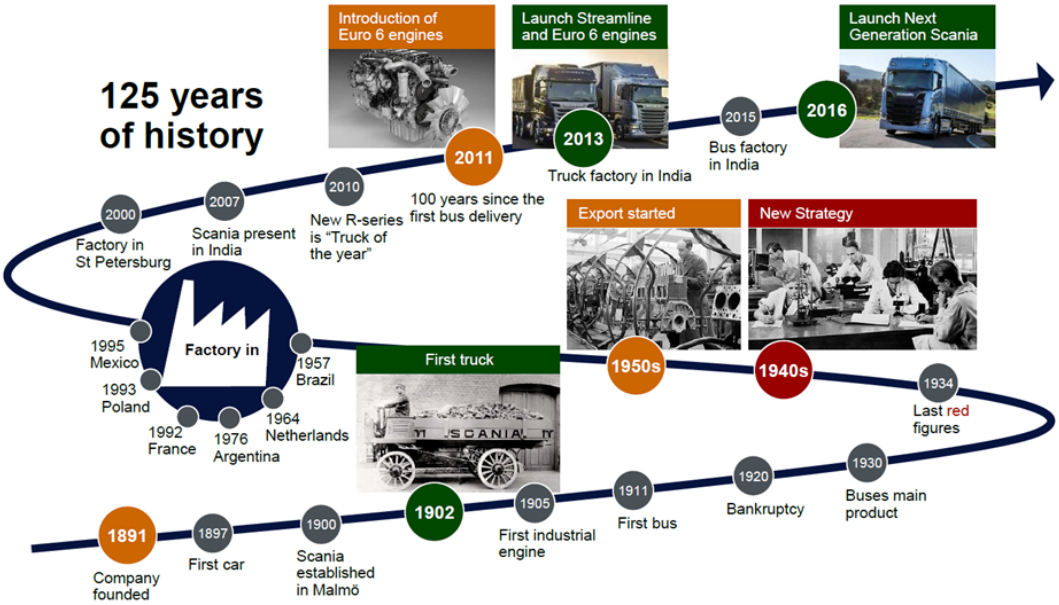

Figure 1.3 - A timeline of Scania's history (Perta, 2017)

1.2.2 The Volkswagen Group

The owner of Scania, the Volkswagen Group, has its headquarters in Wolfsburg and is the largest carmaker in Europe. The Group comprises twelve brands from seven European countries: Volkswagen Passenger Cars, Audi, SEAT, ŠKODA, Bentley, Bugatti, Lamborghini, Porsche, Ducati, Volkswagen Commercial Vehicles, Scania and MAN (Volkswagenag.com, 2017). MAN is, like Scania, a producer of trucks and buses. Volkswagen became majority owner of MAN in 2011, 11 years after they became majority owners of Scania. A goal for the acquisition was to create synergies between MAN, Scania and Volkswagen (BBC News, 2011).

The Volkswagen Group operates 120 production plants in 31 countries. They have 610 000 employees in total that every weekday produce 42 000 vehicles (Volkswagenag.com, 2017).

1.2.3 The modular system

During the early 1950s Scania-Vabis had great problems with component and material deliveries from Germany. Components were incorrectly dimensioned and materials were faulty. The situation became critical and the company was forced to suspend much of its new vehicle and engine development work. The solution to this became a new modular system, a concept that began emerging in the late 1960s. The first truck range produced with the modular system was unveiled in 1980. From a limited number of main components Scania was able to create an almost limitless number of truck variants, adapted to the special needs of individual customers (Scania Group, 2017c). The modular system is still used today and is one of the cornerstones in the production at Scania.

1.2.4 Scania Production System

During the 1980s Scania had problems with people not being happy at their workplace at the same time as quality went down. So far production had been based on instructions from engineers and specialists without a standardised way of working. The production focused too much on results and too little on how to achieve them. To try to solve the problems a collaboration with Toyota was initiated. Toyota had one of the best production systems in the world and helped Scania develop a lean methodology, see figure 1.4. Scania built on the modular system and introduced their first lean program, P90. After a while P90 was further developed and P2000 was born, which had focus on educating the employees on how to manufacture the products without instructions from specialists (Ahrén and Bühlmann, 2015).

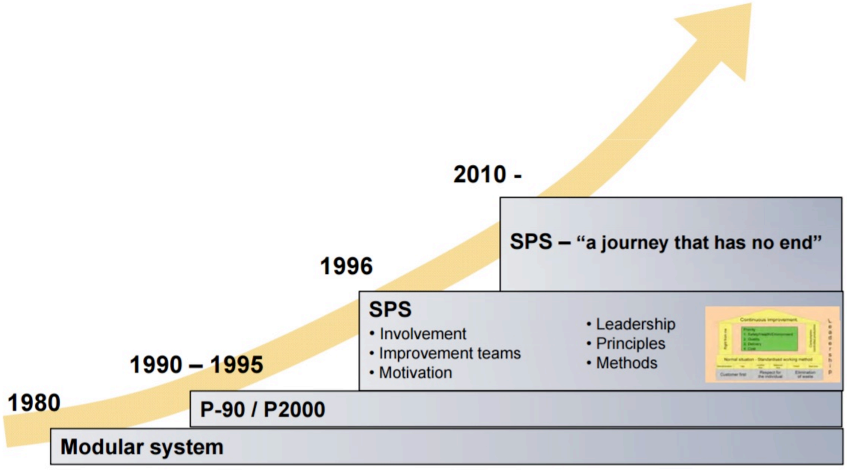

Figure 1.4 - The steps of the lean development at Scania (Palmgren, n.d.)

In 1996, the Scania Production System (SPS) was introduced (Palmgren, n.d.). The production system is illustrated in the SPS house, see figure 5. SPS is based on three main values that the entire organisation is built upon: Customer first, Respect for the individual and Elimination of waste. After these come the four main principles of SPS. They help the employees make decisions that lead them towards a stable and reliable production system where they constantly improve their competitiveness. The four principles are Normal situation - standardised working method, Right from me, Consumption - controlled production and Continuous improvement. In the middle of the house in figure 1.5 Scania's priorities can be seen, briefly mentioned earlier in the report in subchapter 1.1. These are safety/environment, quality, delivery and cost. The priorities should be seen as a compulsory list, the safety should for example be prioritised at the same time as high quality is delivered (SPS booklet, 2007).

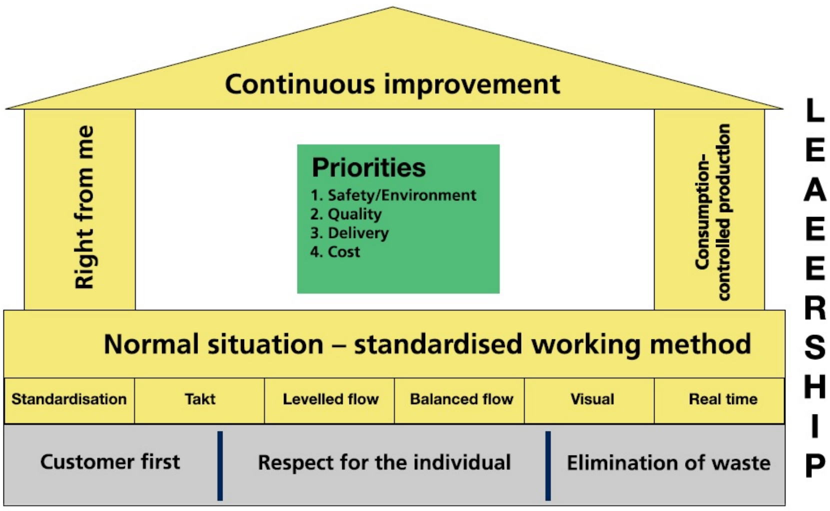

Figure 1.5 - The Scania Production System (SPS) house (SPS booklet, 2007)

1.3 Problem description

Scania is interested in implementing AGVSs in the material handling processes at the company. In order to have a structured approach they want a strategy for how this new technology should be used. There have been earlier cases at Scania where the implementation of new technology at the different production and warehouse sites has been made without a common guideline in the company. An example is when conveyer belts were installed. The lack of a common guideline resulted in different conveyer systems at the different production sites with no standardised equipment.

Scania has noticed the rising trend of AGVs and the advantages with the new machines. AGVSs reduce non-value adding time in manufacturing caused by transportation, increase safety and decrease energy consumption (Bechtsis et al., 2017). They now want a structured strategy of how they should use AGVSs and what technological aspects that are relevant to them.

1.4 RESEARCH PURPOSE, QUESTIONS AND OBJECTIVE

The purpose of the master thesis is to map the technology connected to AGVSs and create a guideline for Scania on how and where to use the technology.

The research questions are:

1. What does the AGVS technology look like today and what innovations are to come?
2. What AGVS technology should Scania use in its material handling process?
3. Which are the major factors that decide whether an AGVS is suitable for a material handling process?

The objective with the master thesis is to create a guideline as a base for a coming strategy. The guideline should be a decision matrix that simplifies the process of deciding which AGVS that is suitable and where. In order to create the decision matrix an extensive mapping of the different technological aspects of the AGVS has to be done. An analysis of the factors in Scania's material handling processes that affects the choice also has to be made.

1.5 FOCUS AND DELIMITATIONS

As this master thesis is written during a time period of 20 weeks some delimitations had to be made. These were arrived at after discussions with Scania regarding what they wanted to prioritize and get out of the master thesis.

The first item that was decided upon was that the report should only cover AGVs in the material handling process within the production area at Scania. More specifically this means from goods arrival at the production site to replenishment of the production line as well as transportation of finished goods from the production line. This means no pure warehouse operations, no other types of automation such as conveyor belts and that deeper studies of assembly AGVs are excluded from the study.

Another item that is not covered more than briefly by this study is load detection technology. Even if it is an interesting topic it is considered to be technology that is added to the AGV and not a part of the core AGVS technology.

The focus of this report is to map the AGVS technology and create a guideline for how and where to use the technology. No specifics will be covered regarding implementation and no calculations will be made regarding the profitability of an investment or the fleet size of the AGVSs.

1.6 Target group

The target group for this report are people with a basic understanding of logistics and an interest to learn more about AGVs. The main target are co-workers at Scania within logistics as well as the members of the appointed project team for the implementation of AGVSs at Scania.

1.7 Report structure

This report is built up according to the following structure:

Chapter 1 - Introduction
Chapter 2 - Methodology
Chapter 3 - Frame of reference
Chapter 4 - Empirical study
Chapter 5 - Analysis
Chapter 6 - Guideline
Chapter 7 - Conclusion
Chapter 8 - References
Chapter 9 - Appendices

In the next chapter of this thesis, Chapter 2 - Methodology, the methodology of the thesis is described. The chapter starts with a description of the methodologies considered applicable for this master thesis. A research strategy is then established connected to how suppliers and reference companies should be chosen. After this the execution of the research done for the master thesis is described, going through how data was collected and analysed. Finally a discussion of the credibility of the report, based on the methodology chosen, is held.

In Chapter 3 - Frame of reference, the theory for the master thesis collected through books and scholarly articles is described. This is done area by area combining all theoretical sources of information. The areas are chosen based on the major topics that are covered by theory. First the different AGV types are described followed by the different technological aspects connected to an AGVS. This is followed by a section about the results that can be expected from an AGV implementation. This subchapter does not cover all results of an AGVS implementation but describes the ones most mentioned in theory. Finally the environmental aspects that affect an AGVS and believed future developments are touched upon. While the section about the future contains many unknowns it is still considered an important part of the report to make the master thesis relevant during a longer period of time.

In Chapter 4 - Empirical study, material collected from interviews with employees at Scania, suppliers and reference companies is presented. The information from interviews with employees at Scania and with reference companies is described interview by interview while the information from supplier interviews is compiled according to the same technology areas as in chapter 3. An additional area that is not covered by theory is added in this chapter. This is called operational aspects.

In Chapter 5 - Analysis, the information gathered from theory and interviews is combined and discussed to get an overall picture and draw conclusions of the information collected. This is done area by area as in chapter 3 and parts of chapter 4.

In Chapter 6 - Guideline, a guideline for how and where to use the AGVS technology in industrial environments is introduced. It is presented in a way so that the reader can get an overview of the possibilities that come with AGVSs and relevant facts that are important to know in an AGV implementation. The guideline is accompanied by a glossary that gives a short description of the specific AGVS terminology.

In Chapter 7 - Conclusion, the research questions stated in chapter 1 are answered. A discussion about the limitations observed after executing the research for the master thesis is also held. Finally areas for future research are suggested and a reasoning about the master thesis' contribution to theory is conducted.

In Chapter 8 - References, the references used for the master thesis are presented in alphabetical order. Referencing is done according to the Harvard System.

In Chapter 9 - Appendices, the five appendices of the report are presented. Appendix A is a table connected to how many publications that have been made on AGVs every year. Appendix B contains the interview guide used for all supplier interviews and appendix C contains the corresponding guide used for all reference companies. Appendix D is a table that contains a full list of the all the interviewees for this master thesis. Appendix E is a glossary of the AGVS terminology.

2 METHODOLOGY

This chapter describes how the research for this master thesis is executed by first going through different methodologies applicable, the strategic methodological choices made and how the report was executed. Finally the credibility of the research is discussed.

2.1 RESEARCH METHODOLOGY

A clear method in a study is important in order to achieve the aim of the study to the greatest extent possible. There are many methods and strategies to choose from. To choose one needs to ask which methods are suitable and of those which is the most efficient (Björklund and Paulsson, 2014 p.49-50). In this case several methods were combined to achieve the aim of the thesis.

2.1.1 Explorative, descriptive, explanatory and normative studies

When choosing which form of study that will be carried out the existing amount of information in the area of knowledge can be important. *Explorative*, or investigatory, studies are often used when there is little knowledge in the field studied and you are attempting to obtain a fundamental understanding. *Descriptive* studies are used when there is a fundamental understanding of the field studied and the aim is to describe, but not explain, relations. An *explanatory* study is used when searching for deeper knowledge about a field of study and the goal is to both describe and explain. Finally, the *normative* study is used when there is already knowledge and an understanding of the field of study and the aim is to provide guidance and suggest measures (Björklund and Paulsson, 2014 p.64).

There is a lot of information about some areas of the AGVS technology but not all. Areas such as guidance on how to program a certain type of AGV are well covered by literature, but there exists very little information regarding what factors that are actually important when implementing an AGVS. The purpose of the master thesis is, like mentioned earlier in the report, to map the technology connected to AGVSs and create a guideline for Scania on how and where to use the technology. The mapping of the technology will be done in a primary phase where an explanatory study is appropriate. The field of AGVSs will be described and explained. In a second phase a guideline for Scania will be created. In this part a normative study is more appropriate as guidance will be provided and measures suggested. This will be done based on the collected information in the primary phase which creates a thorough knowledge and understanding of the field.

2.1.2 Quantitative and qualitative studies

Quantitative studies include information that can be measured or evaluated numerically. Since everything cannot be measured the possibility of conducting studies quantitatively is limited. *Qualitative* studies are used when wanting to create a deeper understanding of the studied problem or situation. The possibility to generalise is however more limited when it comes to qualitative studies than quantitative. It is the aim of the study that decides if it should be quantitative or qualitative (Björklund and Paulsson, 2014 p.69).

To reach the aim of this report a qualitative study was chosen since the absolute majority of the material that will be collected will be hard to measure and evaluate numerically. According to Björklund and Paulsson (2014, p.69) surveys and mathematical models are often better for quantitative approaches and observations and interviews more appropriate in qualitative studies. Because of this interviews was chosen as the main method of data collection for this study.

2.1.3 Triangulation

Triangulation is a valuable and widely used strategy that involves the use of multiple sources to increase the accuracy of a research project (Robson, 2002 p.174). There are according to Denzin (1988, cited in Robson 2002 p.174) four types of triangulation:

- *data triangulation* - the use of more than one data collection method (such as observation, interviews);
- *observer triangulation* - using more than one observer;
- *methodological triangulation* - combining several methodologies such as quantitative and qualitative approaches;
- *theory triangulation* - using multiple theories or perspectives.

Triangulation can create possibilities for discrepancies or disagreements among the different sources which can result in interviews being contradictory (Robson, 2002).

To increase the accuracy in this research project triangulation will be used. Data triangulation will be applied by collecting information from interviews and existing literature. Observer triangulation will also be applied by interviewing suppliers of AGVSs as well as companies that have bought and used AGVSs from some of these suppliers. These companies will act as reference companies and validate the information collected from the suppliers is accurate. Observer triangulation will also be achieved by interviewing several suppliers as they will have different views on what is important when implementing an AGVS and which technology is feasible in what environment.

2.1.4 Chosen method

The method chosen for this report is illustrated in figure 2.1. The map of the technology will be based on data collection from two areas: existing theory and suppliers.

The theory will come from books and scholarly articles on the topic of AGVSs or areas that affect AGVSs. This will be summarized under different areas in a frame of reference part of this report.

The information from the suppliers will be collected through interviews and in some cases visits at their production sites. This will be summarized by different areas in the empirical part of this report. In the **empirical part,** information from interviews with reference companies will also be presented. This will be used to validate information from suppliers and investigate if any statements from suppliers are not correct in the analysis part of the report.

By analysing and comparing theory together with the collected empirical data a map of the AGVS technology will be created. The chapters 3-7 will act as this map. The information from this map will then be combined with information from Scania and the information from theory and suppliers regarding where to implement AGVSs. From this a guideline for how to choose a suitable AGV system and where to implement it will be created.

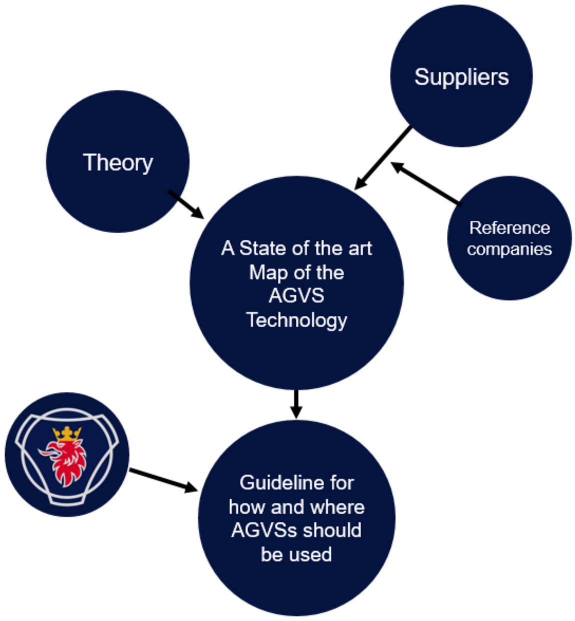

Figure 2.1 - Illustration of the chosen method for the study

2.2 Research strategy

2.2.1 Supplier selection

When choosing suppliers to interview several factors were considered. The most important aspect was to cover a range of different AGVs with different navigation systems and levels of technology. This was considered to lead to the most different opinions regarding what is important when implementing an AGVS and regarding what type of system that should be chosen. These different opinions, compared to each other, would make for a more complete picture of what is on the market and what the advantages and disadvantages with each type are.

This method, to interview a number of suppliers covering a wide range of technologies, led to many possible companies to contact. Meetings in person where the technology would be able to be presented was considered to give an added value. Because of this only suppliers in Europe were contacted with a focus on Sweden and Denmark.

Of the companies contacted there were some that did not answer and one company, Elettric80, that declined an interview as it does not supply AGVSs to the automotive industry. The companies contacted and interviewed were AGVE, DS-automotion, Egemin, Jernbro, Softdesign and Toyota Material Handling. The companies contacted without an answer were Creform, Dematic, Grenzebach and Bastian Solutions.

The chosen companies are considered to cover the whole spectra of AGVs and the technology available in the area.

2.2.2 Reference company selection

Choosing reference companies was done with precision and meticulousness. The aim with this part of the study was to assure that the suppliers had stated was true and to find out if there were any problems connected to the implementation that theory does not cover or suppliers did not bring up. Because of this the criteria for the chosen reference companies was quite specific:

- *Level of experience* - the companies were not allowed to be in an implementation phase of an AGVS. They had to have at least two years of constant use of their AGVS to have a good idea of what the problems during the implementation phase were and how the system has worked after the initial implementation phase.
- *Use AGVs relevant for Scania* - Only users of AGVs that could be considered relevant for Scania were chosen.
- *Company with an AGVS from a supplier interviewed in this study* - To be able to compare information from the company and the supplier only companies where an interview had been conducted with the supplier were chosen.
- *Different fleet sizes of AGVs covered among the reference companies* - To cover a wider range of usage areas of AGVSs companies with different fleet sizes were desired.
- *Different AGVS technology covered among the reference companies* - To cover a wider range of AGVS technology companies with different types of AGVs were desired.

It turned out to be harder than earlier thought to find companies that covered all the criteria. Different fleet sizes was one issue that was difficult to find for example as all the companies that were found appropriate and were willing to be interviewed had between 2-8 AGVs. The companies interviewed were Haldex in Landskrona Sweden, Systemair in Västerås Sweden, and SKF in Steyr Austria.

In addition to these three interviews with reference companies, other companies that use AGVs were also visited. These are however not used as reference companies. The suppliers of the AGVSs at the companies accompanied the authors on the visits in these cases as the visits were part of the supplier visit. As the supplier was present during the visits any questions answered by the user must be considered to possibly be biased. No semi-formal interviews were conducted at these companies either. The visits were at Plastal with AGVE, Volvo Cars with Jernbro and Toyota Material Handling with Toyota Material handling.

2.3 Research execution

2.3.1 Data collection

There are two types of sources in data collection, primary and secondary data. A *primary source* is when new data is collected. This can be an interview or a survey. A *secondary source* is previously collected material by someone else. This can for example be scholarly articles or books (Arbnor and Bjerke, 2009). In this report a combination of primary and secondary sources are used to get an as complete picture of the AGVS technology as possible. This is done through a literature study and interviews.

2.3.1.1 Literature study

The project started with a thorough literature study. First a database search for scholarly articles was made for AGVs in general and later for AGVs and navigation, AGVs and safety, and so on. This was done at the databases Web of Science, Scopus, IEEE, Springer and Elsevier.

By reading articles and studies on AGVs, more articles as well as books on the subject were found. This method is called snowballing (Olhager, 2017) and was used to a great extent. By this method a book called *Automated Guided Vehicle Systems* by Günther Ullrich was found. The book covers many areas connected to AGVSs and is from 2015 which in most cases makes it up to date on the topic. The book does however not cover all relevant areas which is why the parts found interesting have been brought up in this report and complemented with literature from other sources.

A lot of information could be found in literature but far from everything. It could be seen that the majority of the scholarly articles available on the subject are more inclined to describe specific technological aspects of an AGV. The study was therefore complemented by interviews.

2.3.1.2 Interviews

An interview is according to Höst, Regnell and Runeson (2006, p.89) a more or less systematic questioning of a person on a specific subject. There are three types of interview techniques; unstructured, semi-structured and structured. An *unstructured interview* is based on a list of questions and the questions can be asked in a different order and with different words. The interview can lean more in one direction if the interviewee is keener on talking about a certain sub-topic. To make sure that every area in the interview is covered one can decide timeframes for each sub-topic. In a *semi-structured interview* questions with open answers are mixed with questions with only a couple of possible answers. The questions should be asked in the same order with the same words each time to not influence the answers of the interviewee. A *structured interview* is essentially an oral survey (Höst, Regnell and Runeson, 2006 p.90-91).

The interviews that have been conducted for this study have been semi-structured. They have been with employees at Scania, suppliers of AGVSs and with companies that use AGVSs. The interview guide for the suppliers can be found in Appendix B and the guide for the reference companies in Appendix C.

The interviews with employees at Scania were done to get an overall picture of the company and the thoughts people had that could affect the implementation of an AGVS. First of all visits were done at all three production units in Södertälje where informal interviews were conducted with people working there. This was to get an understanding of how the material flow at the production units is organised. To further develop the general knowledge of the company an interview with Tina Arnstedt, Senior Manager at Global Logistics Development at Scania, was conducted. This interview covered Scania's company culture and the company's technological strategy.

At around the same time as this master thesis started a competence group for AGVSs was put together by this thesis' supervisor, Lennart Lundgren. The people in the group have different areas of expertise, all relevant for an implementation of AGVSs. During the execution of the thesis two areas were considered particularly important; IT and safety. IT because there seems to be a lot of problems with the WLAN in AGVS implementations and safety because it is an important area and Scania might have their own requirements on what level of safety that is required. Interviews were conducted with Gunnar Granqvist about IT and Thomas Paulsson about safety to understand their worries and thoughts connected to their area of expertise and AGVSs.

During the course of the master thesis it turned out that there is a dislike for forklifts at Scania. They are considered dangerous and have in some production units tried to be eliminated completely. To thoroughly understand Scania's take on forklifts Ruthger de Vries was interviewed as he was a part of forming the strategy "A forklift free production" at Scania and therefore considered knowledgeable about the subject.

The interviews with suppliers were conducted to understand what the different companies offer and to get a practical view of AGVSs to complement the theoretical knowledge gained earlier. This turned out to be a fundamental part of the report as it was hard to find practical information described in theory. Suppliers were particularly asked about the key operational aspects that affect what type of process that makes a good business case for an AGV implementation. This was done as there was no literature found on the subject and in order to provide Scania with the proper tools to simplify the preparation before an implementation of an AGVS.

The interviews with the reference companies were conducted to see if what the suppliers had said about their AGVSs was correct. As none of the reference companies disagreed with the information that had been given to them by their suppliers no major discrepancies were found. Instead the reference company interviews rather gave additional information on problem areas that could arise and what to think about to decrease the time of implementation for an AGVS.

A compilation of the interviews made for this master thesis can be found in appendix D.

2.3.2 Data analysis

To structure and process the information collected from theory, interviews with suppliers, reference companies and employees at Scania an analysis was made. The analysis was made for two purposes. The first purpose was to discover if anything stated by the suppliers was not true in practice by comparing their statements to the reference companies. The second was to compare theory with the verified empirical data to draw conclusions and create a guideline for how and where the AGVS technology should be used.

The purpose of the first part of the analysis was to discover any discrepancies between the information gathered from the suppliers and the reference companies. This could only be done partly as three reference companies were interviewed compared to the six suppliers. The main contribution from this part was that the reference companies verified parts of the data collected from theory and the suppliers which made this information more reliable.

The next part of the analysis, that was the major part, was to compare theory with the empirical data gathered. This was done with a method called pattern matching which is described by Yin (2009). This is a technique where an empirically based pattern is compared with a predicted one, in this case the theory from literature. Between these, similarities and differences can be found. This was done area by area similarly to how the theory and empirical supplier data had been structured. Based on these similarities and differences an analysis was constructed that discussed all considered relevant areas and took Scania's perspective into consideration. Based on this analysis a guideline for how and where to use the AGVS technology was created.

2.4 Credibility

High credibility in a report means that the conclusions are well motivated, that the study addresses the phenomenon chosen to study and that the results are general (Höst, Regnell and Runeson, 2006). Credibility can be divided into three parts; validity, reliability and objectivity. One should strive to attain as high validity, reliability and objectivity as possible but when designing a study these three areas often need to be weighed against the consumptions of resources (Björklund and Paulsson, 2014).

2.4.1 Validity

Validity is the extent to which one truly measures what is intended, meaning the absence of methodological or systematic errors (Björklund and Paulsson, 2014). To increase validity in a project triangulation can be used (Höst, Regnell and Runeson, 2006; Robson, 2002).

The validity is considered to be high in this report. The intent is to combine theory with the suppliers' views to get the effect of a triangulation. The suppliers are considered to be partly biased since they want to sell their own products which is why reference companies are interviewed to validate what the suppliers state. All interviewed suppliers will probably not be able to be validated because of time restrictions which means that parts of the information will not be validated. Hopefully the information from the suppliers will not differ to a great extent, making it easier to confirm the information from non-validated suppliers with the information from validated suppliers.

2.4.2 Reliability

Reliability is the degree of operational reliability of the measuring instruments, meaning the extent to which one gets the same values if repeating the investigation (Björklund and Paulsson, 2014). Reliability can be improved by using triangulation (Björklund and Paulsson, 2014) and by being thorough when collecting data and doing the analysis (Höst, Regnell and Runeson, 2006). By giving an account for how the research has been done the reader can make his or hers own assessment regarding the reliability of the thesis. One can also let a colleague examine the data collection and analysis so that weaknesses in the research can be found and rectified.

Like mentioned in the previous subchapter, triangulation is used in the report which will increase the reliability. An as thorough account as possible will be given for how the research will be executed to secure that the reader gains in-depth knowledge regarding how the results have been reached. Reliability will also be increased by the fact that the report has two authors that can continually double check and secure the quality of the other author’s work. Based on these actions it is appreciated that the master thesis will result in a reliable result.

2.4.3 Objectivity

Objectivity is the extent to which a person's values affect the study. By clarifying and motivating the different choices made in the report the reader is given the possibility to make his or her own decisions regarding if the choices are reasonable and how the authors have arrived at the conclusion. By this the objectivity is increased (Björklund and Paulsson, 2014).

As the study behind this master thesis is a qualitative one with very little numbers some conclusions might be difficult to draw entirely objectively. As much of the thought process behind the conclusions as possible will however be tried to be accounted for to open up for the reader to understand the decisions made even if he or she does not agree with them. This will hopefully make the report as objective as possible.

3 Frame of reference

This chapter describes the theory collected from books and scholarly articles for the master thesis. First the different AGV types are described followed by an account of the technological aspects connected to an AGVS and the results that should theoretically come from an AGV implementation. Finally the environmental aspects connected to an AGVS are described followed by an account of the probable future of AGVSs. The areas are chosen based on the major topics observed to be covered by theory.

3.1 AGV types

AGVs come in many forms with different attributes and fields of application. What they have in common has tried to be described by many but there is no official definition. According to Müller (1983) an AGV is a driverless transport system used for horizontal movement of materials. Ganesharajah, Hall and Sriskandarajah (1998) define AGVs as battery-powered driverless vehicles, centrally computer-controlled and independently addressable, that are used for moving jobs between workstations on a factory floor. There are many more definitions but what they all have in common is that an AGV is a vehicle that moves material horizontally without a human driver. This can be in a production environment, a warehouse, a hospital or other locations where material is transported.

As AGVs are used in many areas of application they can look quite different and have different attributes. Ullrich (2015, p.132) has the opinion that the best way to categorize AGVs is by looking at the loads they transport. In this chapter a number of AGVs will be described and illustrated in pictures to create an idea of the possible areas of use. First three pallet handling AGVs will be described; Specially designed forklift AGVs, Forklift AGVs as automated serial equipment and Piggyback AGVs. Then the trailer handling AGV, the Towing vehicle, will be described followed by the Underride AGV that handles roller containers. Finally the Assembly AGV that carries assembly objects, the Heavy load AGV that carries heavy weight objects and the Diesel AGV that carries outdoor loads will be described. Ullrich (2015, p.132) also mentions Mini-AGVs and PeopleMovers but these will not be described as they are quite rare and considered irrelevant to this project.

3.1.1 The Forklift AGV

3.1.1.1 Specially designed forklift AGVs

Specially designed forklifts can look as in figure 3.1. This vehicle's load unit is pallets or forklift-compatible containers. It can be used independently or with other AGVs, then managed by an AGV guidance control system (Ullrich, 2015 p.133).

Figure 3.1 - Specially designed forklift AGVs (AGVE, 2017)

3.1.1.2 Forklift AGVs as automated serial equipment

A Forklift AGV as automated serial equipment has the same qualities as Specially designed forklift AGVs but with the difference that it has space for a human to sit or stand in it and steer it manually (Ullrich, 2015 p.134), see figure 3.2 for an example.

The advantage of a Forklift AGV as automated serial equipment is that it can be made out of serially produced vehicles from forklift manufacturers' standard ranges. The serially produced vehicle is enhanced with safety equipment, guidance and navigation components. Some series are more appropriate to automate than others as there needs to be space in the forklift to add all the extra components. The sensors also need to be able to be placed so that the necessary parts of the AGV are covered (Ullrich, 2015 p.134).

According to Ullrich (2015, p.134) there are two camps in the business regarding forklift AGVs. Those who prefer Specially designed forklift AGVs and those who see more advantages in Forklift AGVs as automated serial equipment. He argues that advantages with the first category are that they are designed for permanent use and extended service life, have optimal integration of all additionally needed components, i.e. no space problems, and that they account for an automation-compatible energy concept with the possibility of automatic battery change or charging. Forklift AGVs as automated serial equipment on the other hand come with cost advantages through serial manufacture and have proven service and replacement part availability (Ullrich, 2015 p.134-135).

Figure 3.2 - A serial produced forklift AGV (Toyota-forklifts.eu, 2017)

3.1.2 The Piggyback AGV

A piggyback AGV can look as in figure 3.3. These AGVs can carry pallets, boxes or containers. In contrast to the forklift AGVs mentioned in the previous subchapter this AGV cannot lift the load directly from the floor but requires a certain height which has to be maintained throughout the loading and unloading areas of the AGV. The advantage of this type of AGV is their lateral load handling. They can drive up to the loading area and directly transfer the load without turning and manoeuvring as a forklift would have to. This results in less space needed for loading operations and can be done quickly using the conveyor belts (Ullrich, 2015 p.136).

Figure 3.3 - Piggyback AGV. Source Frog according to Ullrich (2015, p.135)

3.1.3 The Towing vehicle

Towing vehicles tow a number of trailers behind it. Just as with forklift AGVs there are two categories when it comes to towing AGVs. Either they can be specially designed towing AGVs without a space for a human, see figure 3.4, or they can be towing AGVs as automated serial equipment, see figure 3.5 (Ullrich, 2015 p.136). These two categories are by Ullrich (2015, p.136) not separated as trailer-towing vehicles according to him are considerably less common than forklift AGVs.

Figure 3.4 - A specially designed towing vehicle. Source dpm according to Ullrich (2015, p.136)

Figure 3.5 - A serial produced towing vehicle (Toyotamaterialhandling.com.au, 2017)

3.1.4 The Underride AGV

An underride AGV goes under a roller cart or material wagon and lifts it slightly, see figure 3.6 (Ullrich, 2015 p.39). Some underride AGVs can read a transponder on the bottom of the container to get instructions on what the specific cart contains and where it is going (Ullrich, 2015 p.72). Ullrich (2015 p.70) points out that this type of AGV has many advantages over for example forklift AGVs. They require less space than many other AGVs as the container itself determines the space required almost entirely. It also has high manoeuvrability when loading and unloading. This is the standard AGV in environments such as hospitals (Ullrich, 2015 p.132).

An underride AGV can also be used as a towing vehicle. In this case the AGV is equipped with a cylinder (Ullrich, 2015 p.46) or a pickup thorn on the upper side of the AGV that hooks into the roller cart, which remains on its wheels while it is being transported (Ullrich, 2015 p.69).

Figure 3.6 - An underride AGV (Swisslog.com, 2017)

3.1.5 The Assembly Line AGV

Assembly line AGVs carry the assembly object on a path where the object is being constructed during transport. Assembly line AGVs are quite different from transport AGVs. Here the assembly object, its size and weight are very important when choosing AGV. The assembly stages are also important to take into consideration. These AGVs usually have simpler navigation systems than other AGVs and move at a slower pace. Personnel safety also works differently as workers are constantly in direct proximity to the AGV (Ullrich, 2015 p.137). An example of an assembly line AGV can be seen in figure 3.7.

Figure 3.7 - An assembly line AGV (Airfloat.com, 2017)

3.1.6 The Heavy Load AGV

Heavy load AGVs are special AGVs that can handle high weight loads. They are often used in the paper industry when having to transport rolls of paper or in the steel and automotive industry for transportation of steel coils and similar loads. These loads can weigh several tons and are therefore often too heavy for a normal AGV. Vehicles that need to be able to handle such heavy loads place heavy demand on design and components (Ullrich, 2015 p.137-138).

3.1.7 The Diesel AGV

This category includes all AGVs used in outdoor environments. These are often larger AGVs carrying heavy loads. The fact that they operate outdoors allows an internal combustion drive which means that diesel can be used (Ullrich, 2015 p.141).

3.1.8 Special Design AGVs

Besides the earlier mentioned AGVs there are AGVs that are built completely according to the specification of the customer.

3.2 Technological aspects

3.2.1 The AGV guidance control system

An AGVS consists of two parts, the physical AGVs and an overall superordinate system – the AGV guidance control system. The AGVs execute the operational tasks but as they are not fully autonomous and rarely take independent decisions, they need a coordinating system that helps them communicate with each other and with their surroundings. The AGVS also needs to communicate with the internal logistics operating system, e.g. the WMS[2], MRP[3] or ERP[4], to receive orders and information about the entire process. This is done through the guidance control system (Ullrich, 2015 p.124).

Besides these two areas of practice the guidance control system also provides the user with an interface to visualize and interact with the AGVS (Ullrich, 2015 p.122). The Guidance control system connects the different vehicles, the peripheral equipment and the internal logistic operating system.

[2] Warehouse Management System
[3] Material Requirements Planning
[4] Enterprise Resource Planning

It is connected to the internal logistics operating system via a LAN[5] connection and with the vehicles and equipment by a WLAN[6] connection (Ullrich, 2015 p.123). An illustration of the guidance control system is given in figure 3.8.

There are systems where a guidance control system is not needed. These are simple systems where the AGV moves back and forth along a predetermined route and does not require any complex decision making. The system is in this case not autonomous and the AGV requires human interaction to give it orders to move back or forth. An example can be a single towing vehicle that moves trailers back and forth. When it reaches its goal it stops, the employee unloads the trailer and orders it to drive back by pressing a button. The function of such a system is limited and it cannot consist of multiple AGVs that need to communicate with each other, with peripheral interfaces or administer transport orders. The usefulness in such a system is the simplicity, i.e. that it does not need to communicate with other IT systems which makes it easy to implement and handle (Ullrich, 2015 p.122).

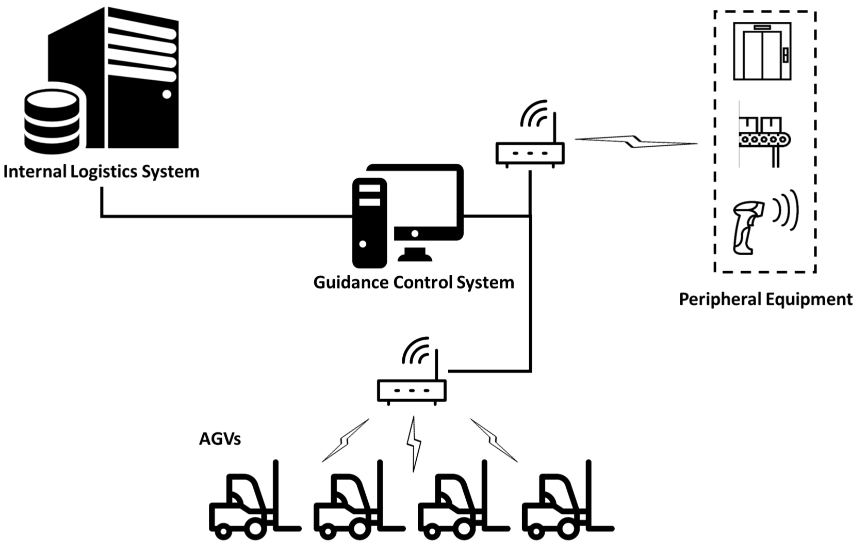

Figure 3.8 - An illustration of the AGVS and how the connects the systems.

3.2.1.1 Transport order processing

The main task of the AGVS is to fulfil transport orders. The guidance control system receives the transporting orders from the user. These can be issued in many different ways, it could be manually by the employees, via the internal logistics operating system or with the use of sensors placed on the load transfer stations where a demand can be recognized (Ullrich, 2015 p.126-127). The information that is received needs to be processed by the guidance control system since the transport order is not clearly defined. It could be “need article A at machine B” which needs to be completed with additional information, such as “pick up from C and bring to D” (Ullrich, 2015 p.125). After this step the transport order is processed in three steps (Ullrich, 2015 p.127):

1. Transport order administration
2. Vehicle dispatching
3. Travel order processing

The transport order administration receives the transport orders when they have been defined and then ranks them according to their priority or their scheduling. It is constantly checked if they are

[5] LAN = Local Area Network
[6] WLAN = Wireless Local Area Network

feasible, if the material is at its source and if the dispatching location is ready to receive the order (Ullrich, 2015 p.127). When the order is ready to be executed its status is updated in the internal logistics operating system and the order is sent for vehicle dispatching.

The vehicle dispatching function has two jobs, deciding which AGV that should execute the transport order and handling empty vehicles (Ullrich, 2015 p.128). When deciding on which AGV in the system that is most suitable for the task a number of methods can be used. The simplest method is to randomly pick an AGV that is free but it can also decide depending on the shortest time or distance to the source, avoiding possible blockages on the route, the chance to pick up several loads from various locations or forecasts of the upcoming system status (Ullrich, 2015 p.128). When a vehicle has fulfilled an order the vehicle dispatching function decides what the vehicle should do next, is there a new order to process, should it return to a waiting area or go to a battery charging station (Ullrich, 2015 p.128).

The travel order processing function plans the path for the AGV and the activities along the path, such as "pick up load at point A then travel to point B, in the intersection that is along the path act in the following way". It ensures problem-free and efficient movement for the AGVs. It then sends the orders to the chosen AGV (Ullrich, 2015 p.128).

3.2.1.2 Service functions

Except for its main task, to process transport orders, the guidance control system aids the user with visualisation and changes to the layout of the operation. It also supports the user with different service functions.

When the AGVS is first set up a map has to be created. The map describes the operating area and the paths that the AGV has to follow, also called the roadmap (Digani et al., 2014). The map is based on a CAD layout of the facility that describes how the facility is structured (Ullrich, 2015 p.129). The roadmap contains all the rules for how the AGVs can move on the map in order to fulfil their tasks. The roadmap is designed to connect the different operational positions with paths that take all the specific environmental aspects into consideration. These can be tasks such as avoiding collision with infrastructure, the direction of certain lanes, load transfer points or stopping points; in other words everything that the AGV must know to safely travel between two locations (Ullrich, 2015 p.129; Digani et al., 2014). An example can be seen in figure 3.9. In addition to creating a CAD layout there is also a more dynamic way of creating a map. This is called SLAM (Simultaneous Localization And Mapping) (Shneier and Bostelman, 2015) and will be further explained in subchapter 3.2.2.2.

Through the guidance control system the map and roadmap can be altered in order to fit a change in the process or to make it more efficient. It also visualises the whole operation in order to see the current status of the operation and any disruptions or errors that occur. This is used to do diagnostics of the system to quickly and safely identify and rectify problems, either by the user on site or by the supplier of the system via distance (Ullrich, 2015 p.129-130).

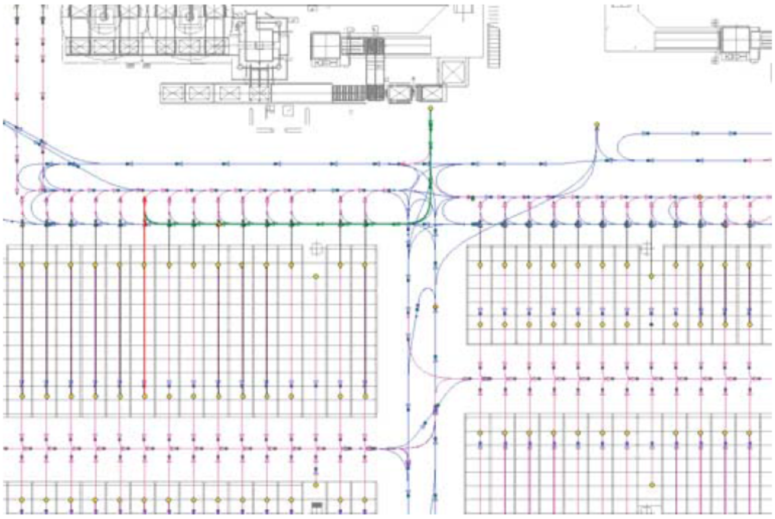

Figure 3.9 - An example of a roadmap with the different paths for the AGVs with all the stock locations (Digani et al., 2014)

The guidance control system collects data on the performance of the operation, e.g. throughput, order processing time and down times. The collected data is used to analyse and optimize the operation (Ullrich, 2015 p.130).

The guidance control system provides a simulation function that can simulate new set ups of the process. This is in order to track the influence of changes in the system and is useful to see if changes are feasible and how they affect the system (Ullrich, 2015 p.131).

3.2.2 Navigation methods

An AGV navigates between different locations in the operating area to fulfil its tasks. In order to do so it must know its own position in its fixed coordination system which is done through different navigation methods (Ullrich, 2015 p.99). Here it is important to note that there is a difference between the terms position and location. A position is an exact set of coordinates that can be matched to the global coordination system of the operating area. A location contains more information than this. It could, for example be information on what the AGV has to do in that position such as stop, communicate with the guidance control system or perform a certain task (Ullrich, 2015 p.100).

The navigation methods for AGVs can roughly be separated into two different groups; fixed-path navigation and open-path navigation (Martínez-Barberá and Herrero-Pérez, 2010a p.1). What is common for the two different groups is that they are both using two methods for knowing their position, dead reckoning and taking bearings. Which method the emphasis lays on is decided by the navigation method (Ullrich, 2015 p.99).

Dead reckoning, also known as odometry, is to some extent used by all navigation methods. It can be explained as a type of blind navigation. By knowing its starting position and by measuring the velocity and the angels of the wheels the AGV can determine where it is relative its starting position (Lee and Yang, 2012). Because of wheel slippage, changes in the radiuses of the wheels caused by wearing and various weights of the load, dead reckoning is imprecise (Ullrich, 2015 p.99). This is why taking bearings is needed for some systems in order to calculate the absolute position of the vehicle. When taking a bearing the AGV is comparing its calculated position to an in advanced known position that was programmed during the setup of the system. By doing this it can correct its calculated position and retrieve its absolute position. Depending on which navigation method that is used bearings are read in different ways (Ullrich, 2015 p.100).

3.2.2.1 Fixed navigation

With fixed navigation the AGV is guided with the help of physical guidelines on or underneath the floor. This can either be by inductive guidance or optical guidance (Ullrich, 2015 p.100-102). For fixed navigation the paths are predefined and navigation is easy as only a sensor is required to detect the guideline. Modifications of the path require physical changes and the system has to be shut down (Martínez-Barberá and Herrero-Pérez, 2010a p.1). The locations in the system are also physical and require special markings that contain additional information for the system. The markings could be metal strips, magnets, tape strips or coloured markings where the AGV is programmed to know what to do when the marking is recognized (Ullrich, 2015 p.156). It can also be more advanced technology such as radiofrequency identification (RFID) tags that can give different instructions depending on the task or the traffic situation (Shneier and Bostelman, 2015). These markings act as bearing points for systems with physical guide paths and are added to the roadmap. Figure 3.10 shows an AGV that navigates along an optical guide path with the help of RFID tags (the green squares next to the coloured line) that give the AGV information on how to act, for example in the crossing that it is moving towards.

Figure 3.10 - The AGV uses optical guiding to follow its path, and RFID tags to handle more complex situations (Turck.de, 2017)

Inductive guidance

Inductive guidance works by creating a magnetic field along the guide path. The AGV measures the magnetic flux and if it measures that it is deviating from the guide path it steers back to the path (Lee and Yang, 2012). Inductive guidance can be both active and passive, where the difference is whether the guide path actively creates a magnetic field or not.

With active inductive guidance a current-bearing conductor is inserted into the floor, about two inches down, which creates a magnetic field. Two coils are mounted underneath the AGV that measures the deviation from the guide path, see figure 3.11 (Ullrich, 2015 p.100).

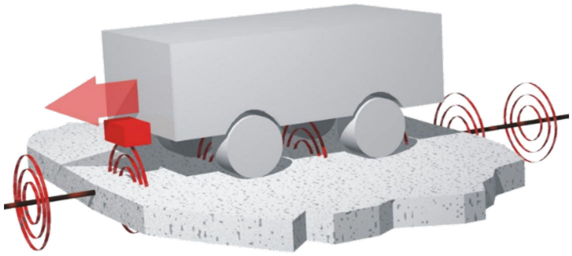

Figure 3.11 - Example of an AGV with active inductive guidance (Goetting-agv.com, 2017)

Passive inductive guidance uses either a metal/magnetic strip or magnetic tape affixed to the floor. The AGV is equipped with two or three magnetic field sensors that detect the strip or the tape, see figure 3.12. The AGV can operate without the guide path with dead reckoning which makes it possible to travel between different paths and makes the AGV less dependent of the condition of the tape or strip (Shneier and Bostelman, 2015).

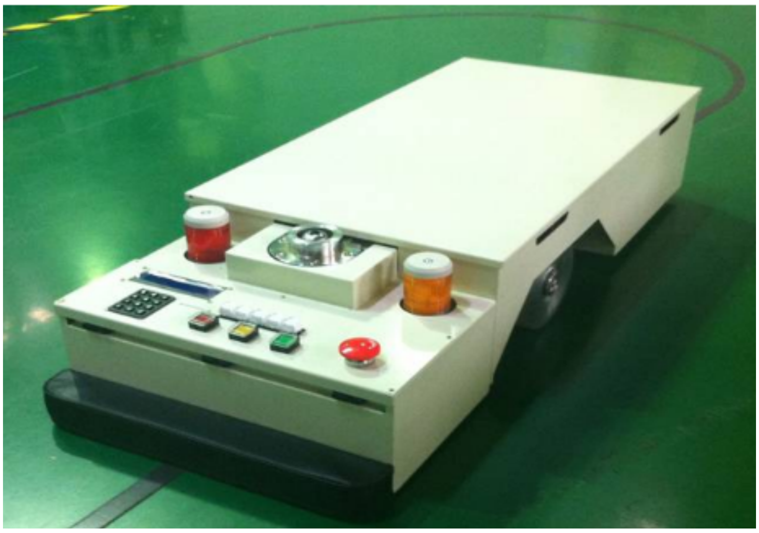

Figure 3.12 - An AGV following a magnetic strip (Ecvv.com, 2017)

The two techniques have different advantages. The embedded wire is more robust since the guide path is protected from tearing caused by overlapping traffic and is not affected by dirt. However, the passive alternative is more flexible since it is easier to modify the path and does not require as much manual work (Sankari and Imtiaz, 2016). Neither passive nor active inductive navigation is suitable if there is metal in the floor since this will affect the magnetic field (Ullrich, 2015 p.101).

Optical guidance

Optical guidance works similarly compared to passive inductive guidance. With a camera sensor underneath the vehicle, the AGV follows a guide path that is either a coloured tape or a painted line. The colour has to contrast the floor in order to detect the edge of the line. This is illustrated in figure 3.13. As passive induction navigation, optical navigation is flexible and is able to operate without the guide path with dead reckoning. It also has the advantage of not being affected by other metals in the floor that would disturb a magnetic field (Ullrich, 2015 p.101-102).

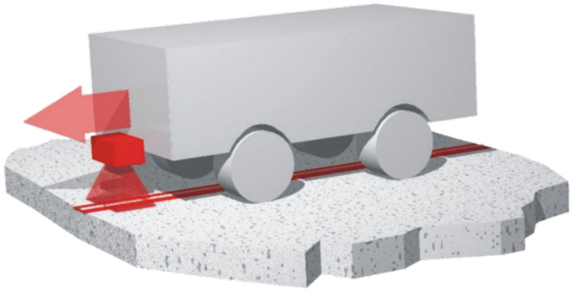

Figure 3.13 - An AGV with optical navigation (Goetting-agv.com, 2017)

3.2.2.2 Open navigation

Open navigation, also called free navigation (Ullrich, 2015 p.103), is a navigation method with no physical guide paths. The guide paths are completely virtual in the roadmap and when changes in the path are required the AGVs only need to be reprogrammed. This results in no extensive manual labour required to change the guide paths (Martínez-Barberá and Herrero-Pérez, 2010a p.1-2). Even if free-ranging AGVs in reality can take any path a roadmap is needed. The limitation to follow certain paths makes the system less flexible but it is required to reduce the complexity of the system (Digani et al., 2014).

Anchoring point navigation

Anchoring point navigation is a group of methods that use dead reckoning and artificial orientation sites in the floor to take bearings. The anchoring point navigation methods are highly dependent on the quality of the dead reckoning unit. There are different examples of anchoring point navigation depending on the artificial orientation objects. The most commonly used is magnet spot navigation (Ullrich, 2015 p.103).

Magnet spot navigation

Magnet spot navigation is a method that uses magnetic anchoring points in the floor for taking bearings (Ullrich, 2015 p.40). The anchoring points are passive permanent magnets that are drilled into the floor and then covered with epoxy, a vinyl layer or painted over. The inexpensive permanent magnets have a length of 5-30mm and a diameter of 8-20mm (Ullrich, 2015 p.103). The AGV is able to take bearings with a magnetic sensor and can locate its absolute position (Ullrich, 2015 p.40). The magnets can be placed either in series or in a grid, see figure 3.14. A grid offers greater flexibility but a series requires fewer magnets (Ullrich, 2015 p.103).

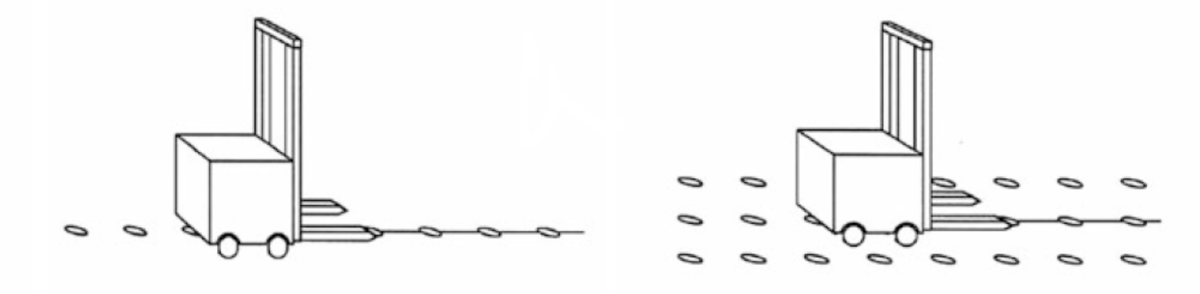

Figure 3.14 - To the left a magnet spot navigation in series, to the right magnet spot navigation in a grid (Ullrich, 2015 p.112)

An alternative to passive permanent magnets are quasi-active transponders. Instead of the magnetic field that the passive magnets generate the anchoring points are quasi-active transponders that are activated by induction from the reading unit beneath the vehicle. This makes the precision much higher, gives the possibility for the AGV to read additional layout information for positioning and more freedom of movement (Ullrich, 2015 p.104-105).

Radiofrequency Identification navigation

RFID navigation is similar to magnet spot navigation with the difference that RFID tags are placed in the floor instead of magnets. The tags are read by an RFID reader mounted on the AGV and can be read from a distance of 1,5 m and by measuring the received signal strength (RSS) an exact position can be determined (Luimula et al., 2009). The system is cheap and simple to implement but it is sensitive to external conditions (Lee et al., 2016).

Laser navigation

With laser navigation the AGV takes bearings in a similar way as a sailboat. It either uses artificial landmarks, that can be compared to maritime navigation with the help of lighthouses or church towers, or natural landmarks that can be compared to islands or strips of land. Artificial landmarks are consequently landmarks that have to be manually installed in the operating area and therefore lead to an increased installation cost (Ullrich, 2015 p.100).

Artificial laser navigation – laser navigation with artificial landmarks

With artificial laser navigation a rotating laser is mounted on top of the AGV. It emits laser that is reflected on retro-reflecting foil (the artificial landmarks) that is mounted on walls and pillars above the workers' heads. The beams reflect back to the AGV and are then scanned. The coordinates of the landmarks are added to the map of the operating area when the system is set up. When the reflectors reflect the laser the AGV is able to triangulate its absolute position based on the knowledge of the coordinates of each reflector, see figure 3.15. At least two or three landmarks need to be visible in order for the AGV to position itself (Ullrich, 2015 p.105-106). Laser navigation is the most prominent method of free navigation since it has high precision and is not restricted by the conditions of the floor (Ullrich, 2015 p.105). The limitations of this method are the increased price for the equipment (Lee and Yang, 2012) and that the design of the AGV is limited since the rotating laser must have a clear line of sight and cannot be in the same level as personnel (Sobreira et al., 2016).

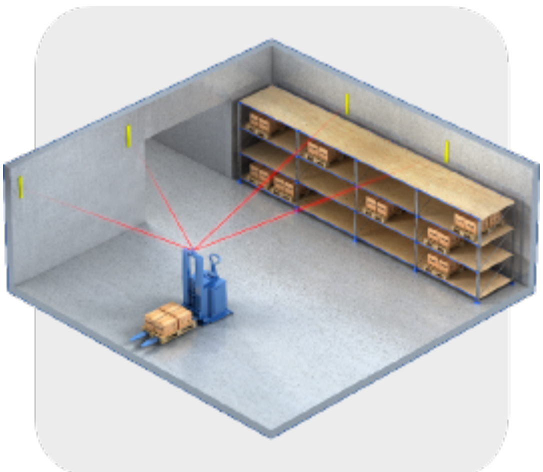

Figure 3.15 - Illustration of laser navigation with artificial landmarks (NDC Solutions, 2017)

Contour navigation – laser navigation with natural landmarks

Contour navigation is when reflectors are not used to determine the position of the AGV. Instead the AGV uses the already existing environment within the facility to navigate by, which is why it is called contour navigation. The advantage with this technique is that it is not bound by external reflectors that have to be calibrated and inserted into the guidance control system. This makes the system even more flexible than artificial laser navigation. The most common type of contour navigation is to use a laser that scans the environment and recognizes walls, pillars and other fixed items, see figure 3.16 (Ullrich, 2015 p.107). The downside is that the precision and robustness of the system are lower than for artificial laser navigation (Ullrich, 2015 p.107-109).

Figure 3.16 - An illustration of contour navigation (NDC Solutions, 2017)

Sobreira et al. (2016) describe in their article *Robust Mobile Robot Localization based on Security Laser Scanner* a way of combining the safety laser scanner that is required on the AGV with the navigation scanner. This decreases the price of the vehicle and the amount of sensitive equipment on the AGV. Ullrich (2015) mentions this as an important part of the future of AGVSs. By combining the navigation and the safety functions the AGV can become even smarter and new areas of application can be found.

Contour navigation can be used in different ways. One alternative is to have a distance-measuring laser in order to drive along walls. This acts as an aid to other navigation methods. When the laser scanner is allowed to move around a third axis, it is possible for the scanner to create a 3D-image of the environment, compared to the regular 2D image. This makes it possible to navigate by scanning the ceiling, either with bar codes in the ceiling or a mosaic image of the ceiling (Shneier and Bostelman, 2015).

In order for contour navigation to work the AGVS needs an internal map of the environment. This can be obtained in two ways. Either manual scanning is done by a person or a technique called SLAM (Simultaneous Localization and Mapping) can be used. This means that the laser that is used for navigation also maps the unknown environment by measuring distances to different objects (Riisgaard and Blas, 2005 p.6). By using SLAM the system becomes more flexible and easier to use in new and/or dynamically changing environments since there is no need for designing the map manually (Klančar et al., 2017 p.402).

SLAM technology combines odometry, laser scanners and an extended Kalman filter (EKF). The AGV travels around in the new environment and detects new objects with the help of the laser scanner. Thanks to its odometry it can have a fairly good sense of its position. Since the odometry of the robot is often erroneous it cannot be fully relied upon which is why an EKF is used. The EKF compares the believed position, calculated by odometry, with how the detected objects move when the robot is moving (Riisgaard and Blas, 2005 p.10). In this way it is able to map its operating area and after that calculate the collision-free paths in the map. By letting the laser rotate around an additional axis or by installing another scanner a 3D map of the environment can be constructed instead of the 2D map that a regular scanner creates (Shneier and Bostelman, 2015). Using SLAM makes the system much more flexible since it can adapt to new environments in a quick and easy manner (Klančar et al., 2017 p.402). The equipment is however expensive and if a 2D scanner is used obstacles that lay above or below the scanner are not detected (Zunino, 2002). Some materials that are transparent, such as glass, cannot be detected by the laser either (Zunino, 2002).

There are alternative methods to laser scanners. Both sonar and vision by camera can be used. Sonar is cheaper than laser scanners but the precision is not as good. It can also be affected by many factors that will lead to a bad result (Zunino, 2002). Vision by camera has a clear advantage since it allows the robot to retain a larger amount of information. With a colour or grayscale image it can identify objects and other features in the environment that laser or sonar cannot (Zunino, 2002). The disadvantages with vision is that it is expensive, highly influenced by lighting and has computing requirements. When using laser or sonar the information is much better defined and therefore it is better suited for AGVSs (Zunino, 2002).

GPS navigation

Most open navigation methods use passive markers, such as reflectors or passive magnets, for taking bearings. The most common active technology that is used for taking bearings is the GPS system (Ullrich, 2015 p.100). Just like with automobiles, satellites are used to determine the position of the GPS receiver. The issue with GPS navigation is that a clear line of sight to the sky is required, which is not the case in an industrial environment. This makes GPS navigation problematic for AGVSs (Ullrich, 2015 p.100). A way to solve this is by installing a local positioning radar (LPR) that is used instead of the satellites to determine the position (Ullrich, 2015 p.110). The issue with using LPR is that the precision of the AGVS is diminished to at the most +-10 cm. GPS navigation is best used outdoors, in harbours for example, where laser navigation or fixed-path navigation cannot be used (Carlo, Vis and Roodbergen, 2014).

3.2.3 Obstacle avoidance

Flexibility is one of the main goals with AGVSs. AGVs are designed to move from one location to the next, and since they are moving in real environments unforeseen events will occur (Digani et al., 2014). An issue with the technology today is how to avoid obstacles in a secure manner. With today's applications the robot is designed to stop if an obstacle blocks the guide path. The two applications *navigation* and *safety* are not combined which results in the AGV moving as a blind person, moving along its path until the safety sensor detects an obstacle and the AGV stops. This can be compared to how humans instead are able to predict future obstacles and can alter their paths before they have to stop (Ullrich, 2015 p.169-170). According to Ullrich (2015) the blind navigation has its advantages as well. Even if the system is less flexible it becomes more predictable which is an important factor for safety reasons. When operating in the same environment as manual driven forklifts or pedestrians it is important for personnel to be able to know how a robot will act. Ullrich (2015, p169-170) does however mention that avoiding obstacles is a function that is important for the future of AGVSs. When the AGV is working in a restricted environment where only adults and trained personnel are operating today's technology is sufficient, but if the AGV could be able to "open its eyes", as Ullrich (2015, p.169) calls it, and were able to combine the navigation and safety applications a whole new scope of use for the AGV could be identified (Ullrich, 2015 p.170).

In the article *Obstacle Avoidance for Industrial AGVs by* Digani et al. (2014) a method for obstacle avoidance is presented and simulated. The method is divided into four steps for the AGV to safely pass an obstacle. The method is simulated but never tested in an industrial environment.

3.2.4 Safety

Safety is an extremely important aspect of an AGVS. To ensure that no harm is done to people or objects several regulations are strongly recommended to be followed by suppliers. These state the minimum safety technology that an AGV should have. The most central regulation is called EN 1525. This regulation is quite old, from 1997, but is still in use (Ullrich, 2015 p.118-119). Ullrich (2015, p.118-119) lists what he thinks are the key technological safety features from the EN 1525 that an AGV should have. These are:

- An emergency stop switch. This has to be accessible and easily recognizable to everyone.
- A combination of optical (rotating warning lights) and acoustic warning signals. This includes blinkers to indicate change of direction as with automobiles but often with acoustic support.
- Mechanical independently operating brakes to ensure proper stopping. They should be intrinsically safe which means that they need an energy supply in order not to activate while driving. The brakes must be able to stop the AGV with a maximum payload and incline of the drive path or slope.
- Kick plates and special safety equipment for load handling. This is to ensure safe operations.
- A personnel protection system. It has to ensure that people or objects located in the drive path are recognized and that the AGV stops before these are injured or damaged. These systems can either be mechanical that react to contact or contact-free sensors that scan the area ahead using laser, radar, infrared or ultrasound and stop if there is something in the pathway. If mechanical the contact with a human may not exceed 750 N and the AGV needs to shut off at contact.

Figure 3.17 - AGVs with wire mesh as bumpers from Ameise and Teletrak (Source E&K (1965) according to Ullrich (2015, p.3)

The most central and technologically advanced feature of the AGV safety system is the personnel protection system. A couple of decades ago this consisted of tactile sensors. This meant physical bumpers and emergency arrest handles with mechanical switches (Ullrich, 2015 p.2). They consisted of metal bales or wire mesh in the beginning, see figure 1.1 and 3.17, and then advanced to plastic bales and soft foam in the 70s and 80s, see figure 3.18.

Figure 3.18 - Personnel safety features: left Plastic bale (Dannemark, 2017); right soft foam bumper (Source MLR according to Ullrich (2015, p.119))

Figure 3.19 - The S3000, S300 Standard and S300 Mini (Source SICK according to Ullrich (2015, p.120)

The safety features have now been modernized and consist of advanced laser sensors. Most of these are produced by a company called SICK (Ullrich, 2015 p.120). Figure 3.19 shows an example of what some safety sensors from SICK look like. The areas of use for the devices differ in the possible driving speeds and the resulting stopping distances. They have protective radiuses from 2-7 meters (Sick.com, 2017b). The protective areas adapt to the situation to account for change in speed, direction, curves and docking manoeuvers (Ullrich, 2015 p.2). The safety fields are illustrated in figure 3.20. The yellow and orange areas are warnings fields. When the AGV detects a person or an object in this field it slows down. If a person or an object is detected in the red field, called the protective field, it stops (Sick.com, 2017a). Technologically the safety scanners work by scanning their surroundings and measuring distances by using a time-of-flight principle[7]. The integrated rotating mirror creates a two-dimensional scan for freely defined protection areas (Sick.com, 2017b). The safety scanners have a safe data communication interface that allows them to exchange guidance signals with other vehicles (Ullrich, 2015 p.2).

[7] The Time-of-Flight principle is a method for measuring distance. A short laser pulse is sent out and the time until it returns is measured. The distance from the object hit is given by $D=½*c*T$ where c is the speed of light and T is the roundtrip time (Zunino, 2002).

Figure 3.20 - Safety fields for an AGV (Sick.com, 2017a)

With all these safety features there are still areas in the operation of an AGV that can be dangerous, for example the load-transfer. According to Ullrich (2015, p.156) the simplest approach to make sure danger to people is avoided here is to restrict access to relevant areas. Where this is not possible, floor markers or designated danger zones can be employed. Visual and acoustic warning signals can also be used together with special sensors to recognize persons and other obstacles. Intersections are also areas where it can be useful to introduce extra safety measures like traffic lights or parabolic mirrors if AGVs and humans are to work in the same area.

3.2.5 Batteries

AGVs are usually run on electrical power with a battery that has to be charged. Outdoor and larger AGVs that can transport loads of several tons are sometimes run on diesel (Ullrich, 2015 p.141).

The most common batteries found in AGVs are according to Ullrich (2015, p.150-154) lead-acid batteries (liquid electrolyte), lead gel batteries (bound electrolyte) and nickel-cadmium batteries (liquid electrolyte). Ullrich (2015, p.150-154) states that there are more modern batteries such as nickel metal-hydride and lithium-ion but that they are not a part of the technological standards for AGVs. They will be described here anyway due to fast development in the technological industry and that they, according to the empirical studies described later in this report, have started to be used in the industry.

In table 1[8] the different battery types are compared to each other based on information from Larminie and Lowry (2012). The specific energy is the amount of electrical energy stored for every kilogram of battery mass and the energy density is the amount of electrical energy stored per cubic metre of battery volume. The specific power is the amount of power obtained per kilogram of battery.

[8] Worth to note is that this information is from 2012 and many of the batteries have been further developed during the last five years. The table is included to create an image of the differences between the batteries.

Table 3.1 - A compilation of battery types and their qualities

	Lead-acid	Nickel-cadmium	Nickel metal-hydride	Lithium-ion
Specific energy (Wh kg-1)	20-35 depending on usage	40-55 depending on current	~65 depending on power	140
Energy density (WH l-1)	54-95	70-90 depending on current	~150	250-620
Specific power (W kg-1)	~250 before efficiency falls greatly	~125 before becoming very inefficient	200	300-1500
Operating temperature	Ambient, poor performance in extreme cold	-40 to +80 degrees C	Ambient	Ambient
Number of life cycles	Up to 800 to 80% capacity (Forklifts specifically: up to 1200-1500 cycles over 7-8 years, 7-8 h operation in one charge)	1200 to 80 % capacity (sometimes up to 2500)	~1000 to 80% discharge	>1000
Recharge time	8 h (but 90% recharge in 1 h possible)	1 h, rapid charge to 60% capacity 20 min	1 h, rapid charge to 60% capacity 20 min	2-3 h, but can be charged to 80% of their capacity in under 1 h

3.2.5.1 Lead-acid batteries (Pb-acid)

Traditional lead-acid batteries

According to Berg (2015, p.48) the lead-acid battery is the most widely used battery in the automotive industry, employed as the power supply for the starter engine and as voltage regulators during vehicle use. They are also one of the most common battery types in AGVs (Ullrich, 2015 p.150-154). Pb-acid batteries are the cheapest rechargeable battery per kilowatt-hour of charge (Larminie and Lowry, 2012) and have more than 140 years of development behind them which makes them a reliable and robust technology (Berg, 2015 p.48). They are designed to be deep cycle discharged meaning that the depth of discharge should be high (McHaney, 1995).

Since lead is a heavy metal the technology itself becomes heavy and bulky (Berg, 2015 p.48). Lead can have, if let out in nature, a strong environmental impact. This makes it a prohibited battery in some applications but has in most cases resulted in lead-acid batteries being one of the most recycled products in the world (Berg, 2015 p.48).

When it comes to maintenance, traditional lead-acid batteries require topping up with distilled water from time to time (Larminie and Lowry, 2012).

Lead gel batteries

Lead gel batteries are a type of Pb-acid battery. To overcome deficiencies of the electrolyte, i.e. gassing or evaporation, sealed Pb-acid cell designs have been developed. Lead gel batteries is a type of sealed battery. Here a gel-like electrolyte is used where the gel acts as both electrolyte and separator. The charge rate is limited in order to prevent gas evolution and decomposition of the gel, which could damage the cell (Berg, 2015 p.52). According to Larminie and Lowry (2012) this type of Pb-acid battery is used more in electric vehicles as it is more robust than normal lead-acid batteries and can withstand deep cycling. Unlike traditional lead-acid batteries it is not necessary to top up gel batteries with distilled water and the maintenance needed is lower.

3.2.5.2 Nickel-cadmium batteries (NiCd)

The nickel-cadmium battery was, when introduced, considered to be one of the main competitors to the Pb-acid battery for use in electric vehicles (Larminie and Lowry, 2012). They have nearly twice the specific energy of Pb-acid batteries, see table A, but can cost up to three times as much. The higher cost is however offset to an extent by its longer life cycle. Just as with Pb-acid batteries, NiCd batteries need to be properly charged (Larminie and Lowry, 2012).

Due to the high content of the heavy metal cadmium in NiCd the batteries are environmentally harmful. The NiCd technology has even become forbidden to use in some applications due to this (Berg, 2015 p.52).

3.2.5.3 Nickel metal-hydride batteries (NiMH)

The nickel metal-hydride battery technology was commercialised as late as 1989 for portable computers and cellular phones. In the years after it continued to be popular but experienced a rapid decline as the more energy dense lithium-ion battery was introduced. NiMH is still widely used as energy storage systems in hybrid electric vehicles. The technology was developed for environmental reasons and can be seen as a development of the NiCd battery (Berg, 2015 p.52). The NiMH battery has higher energy density and power density than NiCd and is possible to charge somewhat faster (Larminie and Lowry, 2012). It is slightly more costly than the NiCd battery (Larminie and Lowry, 2012) but the materials used are environmental friendly (Berg, 2015 p.52).

Normally several hundred thousands of cycles can be achieved with a NiMH battery. They are robust and tolerant when it comes to different temperatures but can emit gas (O2 and/or H2) if stored or not used right. Because of this the battery needs safety vents for protection (Berg, 2015 p.53).

3.2.5.4 Lithium-Ion batteries (Li-ion)

Lithium is the lightest metal in the periodic table and has a low electrochemical potential which makes it one of the most reactive metals (Berg, 2015 p.57). There is a range of lithium batteries such as lithium metal, lithium ion, lithium ion polymer, lithium oxygen and lithium sulphur (Berg, 2015 p.58-60). In this report only lithium ion will be covered since it, compared to the other lithium batteries, has become the most common battery for electric vehicles (Berg, 2015 p.58).

Lithium batteries generally have low weight and high energy density. Many cycles can be achieved and fast charging is possible (Berg, 2015 p.58). The Li-ion batteries were in 2012 predicted by Larminie and Lowry (2012) to have approximately ten times higher specific energy than Pb-acid batteries in 2020. For most types of lithium batteries the temperature must be controlled since the electrolyte can be unstable. This may lead to capacity loss or thermal runaway. Overcharging the cell may lead to the same phenomena. To reduce these risks lithium batteries contain a protective circuit to control currents, temperature and voltage levels in order to shut the battery down if abused.

3.2.6 Charging

AGVs have to be supplied with energy for the purposes of navigation, sensory systems, the mechanical moving components and the load transfer equipment (Ullrich, 2015 p.150). The way the AGVS is charged can have a significant impact on the way a material handling system operates. Charging at inconvenient times can affect operational time and increase the size of the AGV fleet needed (McHaney, 1995). According to McHaney (1995), battery usage is often omitted in AGV research which can lead to misleading simulations. He does however also argue that there are certain circumstances where battery constraints do not affect operational output. These instances include systems with naturally occurring breaks, shift changes coinciding with battery swapping or charging, systems with high amounts of idle time and systems where charging can be regulated and ensured to take place without impacting the system. If AGVs can be fitted with batteries sufficiently sized to last an entire shift and if arrangements can be made to swap or charge AGV batteries during off-shift time, this will not impact the system and charging does not need to be taken into account when considering the size or type of the AGV fleet.

3.2.6.1 Charging methods

According to Ullrich (2015, p.150-154) there are three usual methods of charging used by the AGVSs that are in use today. These are charging traction batteries, non-contact energy transfer and hybrid systems.

Charging traction batteries is the first method mentioned by Ullrich (2015, p.150-154). This is the classical charging method used in most areas of technology today. Here the AGV is charged at a charging station by having contact with an energy source.

The second method of charging is non-contacting energy transfer which is done through induction. Here a conductor in the form of a single coil is mounted in the floor, running along the route of the AGV. The secondary circuit is mounted close to the floor in the AGV where the induced energy is made available to the vehicle. The charging is done through the gap in the air and is maintenance and wear-free. This method of supplying energy is good for simple AGVS layouts as the coils need to be placed in the floor where the AGV is going to move (Ullrich, 2015 p.150-154).

The third method that Ullrich (2015, p.150-154) mentions is a hybrid system. This is an energy supply system consisting of non-contacting energy transfer and an auxiliary battery. The auxiliary battery is considerably smaller than the traction batteries mentioned earlier and fulfils only limited tasks. The reasons for why an auxiliary battery can be useful are for example that sometimes all areas of a layout cannot be equipped with a double conductor. This makes the possibility to use a battery in certain areas very useful. It can also be useful in the event of a breakdown where the vehicle could be driven off the layout using the battery without disturbing the other AGVs.

3.2.6.2 Charging schemes

McHaney (1995) presents five different charging schemes for AGVSs. These will be presented below and are manual battery swap, automatic battery swap, opportunity charge, automatic charge and combination charge. All information in this subchapter is from (McHaney, 1995).

One of the most basic AGV battery schemes is the manual swap. When the battery level falls below a certain percentage the AGV is routed to a station where the battery is manually changed to a fully charged one.

The automatic swap is similar to the manual one but with a machine that is used to change the battery instead of a human. The automatic swap operation takes in most cases less time to complete than a manual swap.

Opportunity charging is the use of natural idle time to replenish batteries. This is used when AGVs have many short predictable stops. Battery chargers are located at or near the AGV's stop locations and the AGVs charge while waiting for their next task. If planned correctly opportunity charging has little or no effect on the operation time since existing idle time is used. This means that the number of needed vehicles will be unaffected.

In AGVSs with non-predictable routes and little opportunity for charging, automatic charging can be used. With this scheme the AGV will run until the battery has depleted to a certain percentage. At this time the AGV will go and charge its batteries in a charging station where it will remain until the battery is recharged to an acceptable level. Automatic charging may have an effect on the number of AGVs needed in a system as time for battery replenishment is added to the AGV operation time. Pb-acid batteries are often used in case of automatic charging or battery swapping since they are designed to be deep cycle discharged.

Combination charging is a crossing between opportunity and automatic charging. This can work in two ways. Either the AGV can operate with an opportunity charge system but when a depletion to a certain percentage is reached the AGVs are routed to a charging station where they stay for a longer duration. The other version is also based on the opportunity charge scheme but with the feature that when an AGV starts to charge it is held there until its battery has been returned to an acceptable level. A combination approach may increase the AGV fleet but not as much as with automatic charging as idle time is used.

3.3 Results of implementing AGVs

3.3.1 Safety aspects

According to Ullrich (2015, p.114-121) legislation connected to AGV safety in the European Union is the strictest in the world. Lawmakers, institutes in charge of norms and standards, the VDI[9] and insurance associations all maintain a package of technical regulations to minimize potential harm to workers caused by AGVSs. This has been very successful and so far there have been almost no accidents reported caused by AGVs.

Forklifts on the other hand have led to many accidents during the years. According to Arbetsmiljöverket (2016, p.89), 602 work accidents and 169 occupational diseases[10] with sick leave for forklift drivers were reported in Sweden in 2015. This gives a total of 771 cases of sick leave during 2015 connected to forklifts. The same number was 786 in 2014 (Arbetsmiljöverket, 2015). Arbetsmiljöverket (2016, p.23) also states that accidents connected to forklift drivers in 2015 was the thirteenth most reported type of work accident in Sweden with 23.5 of a 1000 male forklift drivers[11] reporting an accident in 2015. The most common reasons for work accidents are loss of control of the vehicle, collision, overturning, use of the forklift in an incorrect way, squeezing of feet or legs and repetitive strain injuries on the neck, shoulders and back (Av.se, 2015).

What is even more serious is that since 2008 there have been nine deaths connected to forklifts in Sweden, which is about one per year (Arbetsmiljöverket, 2017; Arbetsmiljöverket, 2013). The accidents are most often connected to workers being hit by forklifts, forklifts overturning or accidents connected to loading or offloading material on the forklift.

Although Bechtsis et al. (2017) claim that AGVs are safer than normal forklifts in material handling processes, no formal study that actually proves this has been found. What has however been compared is how much safer self-driving cars are compared to human-driven vehicles. Blanco et al. (2016) at the Virginia Tech Transportation Institute have compared the amount of accidents connected to Google's self-driving cars and normal human-driven vehicles. Since self-driving cars have not been on tested for so long parts of the results cannot yet be statistically proven. They have however concluded that there are 4.2 crashes per million miles for human-driven vehicles and 3.2 for self-driving cars in the United States of America. This is for what they call level 1 and 2 crashes that includes crashes that cause sufficient property damage to be reported to authorities, crashes

[9] VDI is the German engineering association (Vdi.eu, 2017).

[10] Occupational diseases are injuries caused by other injurious actions than work accidents, for example by repetitive one-sided actions or mentally straining circumstances in the workplace.

[11] There is no corresponding data for women as there are few female forklift drivers compared to male ones. This leads to insufficient data to be able to make a statistically correct analysis in this case.

that reach an acceleration greater than +-1.3 g, most large animal and sign strikes and any crash above this in severity. According to this information crashes with human-driven vehicles happen 31 per cent more times per driven mile than with self-driving cars.

3.3.2 Energy aspects

While there is literature that states that the energy consumption goes down with an AGVS, it is hard to find actual proof or studies made about this. An area that has gotten more attention is however the energy results of automation within the automotive industry. Wadud, MacKenzie and Leiby (2016) have done a study on highly automated vehicles and have concluded that automation can affect energy consumption in multiple ways, positive and negative. This is illustrated in figure 3.21 where the positive and negative percentual changes in energy consumption due to automotive vehicle automation can be seen. Factors that Wadud, MacKenzie and Leiby (2016) argue increase energy consumption are higher highway speeds, travel cost reduction, new user groups[12] and increased features. Increased features in this case refers to the fact that travellers might start devoting more time to other activities in their vehicles, thus being able to travel greater distances and spend more time in the vehicles. These additional physical vehicle features also weigh a lot which increases energy consumption. Factors that decrease energy consumption are among others eco-driving and improved crash avoidance. Eco-driving is in this case the minimization of repeated braking-acceleration cycles since breaking represents wasted energy (Barth and Boriboonsomsin, 2009). Whether these factors are relevant to AGVs will be discussed in the analysis (chapter 5) in this report.

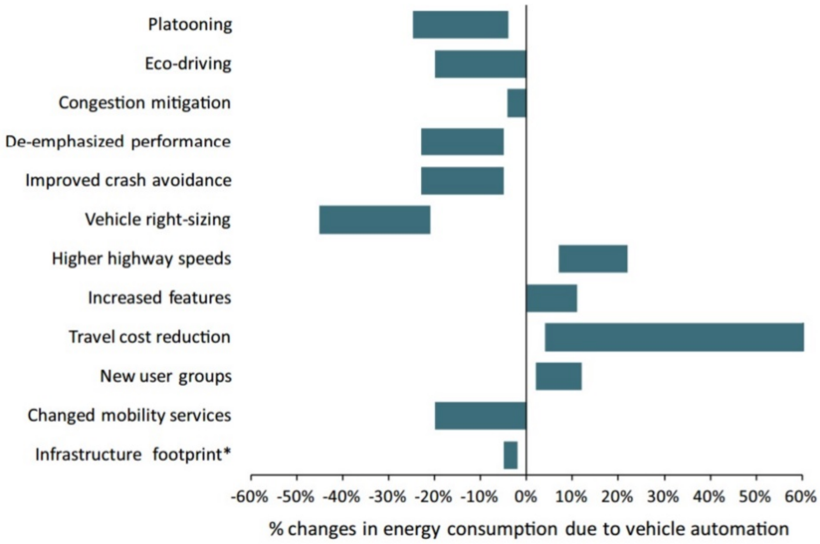

Figure 3.21 - Summary of estimated ranges of operational energy impacts for automation of automobiles through different mechanisms.

3.4 Environmental aspects

When deciding how to design an AGVS there are many factors to take into account. How the process is designed is essential, where factors such as what load carrier, weight and throughput have to be taken into consideration. What also is important is to not underestimate the effect of the environmental factors caused by the setting the system operates in. According to Ullrich (2015, p.154) many projects end up with repairing mistakes that could have been avoided with a more

[12] People that have disabilities or health problems that make them unfit drivers could start using fully automated vehicles.

thorough planning phase. The environment that the AGV operates in limits the amount of different possible versions of vehicles suitable for a specific process. In Ullrich's (2015) book he mentions different environmental aspects that have to be taken into consideration. These are:

- The climate
- Scarcity of space
- Overlapping material flows and pedestrians
- The condition of the floor

Besides these factors Wilamowski and Irwin mention in their book *Industrial Communication Systems* (2011) the issues of a well-functioning WLAN connection in an industrial environment. The guidance control system is depending on a stable WLAN connection (Ullrich, 2015) and it is therefore an important factor to take into account.

When the AGV operates in a climate that varies from the norm the use of certain navigation and safety systems will be restricted. Ullrich (2015, p.155) lists some conditions that, according to him, counts as varying from the norm:

- Especially high or low temperatures, less than 5 degrees Celsius and above 30 degrees Celsius.
- Large temperature fluctuations
- High humidity or extremely dry air
- Contaminants in the air, such as oil vapour, steam or dust
- Varied lighting conditions

These conditions disturb the navigation and safety systems in different ways. Varied lighting or humidity can for example interfere with the laser scanners, both for navigation and safety. Temperatures below zero degrees Celsius can also be a problem causing slippage and result in failure of the safety system (Ullrich 2015, p.155).

It is these factors that makes AGVSs for outdoor applications such a challenge (Ullrich 2015, p.28). AGVs for outdoor use have to be able to face extreme weather conditions such as snowfall, heavy rain and wind; conditions that prevent the system from working reliably and safely. Outdoor use also causes more wear and tear on the vehicle components. AGVSs for outdoor use are therefore restricted to use mechanical safety systems, such as foam bumpers and plastic roll bars that limit the driving speed of the vehicle. Since laser is not a reliable alternative in environments with sunlight laser navigation is not an option. Instead methods such as GPS or magnet spot navigation are better suited (Ullrich 2015, p.28-30).

An AGV often operates in an environment where space is restricted which will affect the possibility to use AGVs and the performance of a system. According to Ullrich (2015, p.154) the VDI Guideline 2510-1 recommends that the AGV has 50 cm clearance on each side and if there is oncoming traffic another 40 cm on one side. This it to be able to operate smoothly and not cause any bottlenecks.

Employees and AGVs are often operating in the same area. The employees need to be instructed on how to interact with the vehicles and learn how they work. During the first two weeks after implementation the efficiency of an AGVS sometimes decreases since there is a great deal of stop-and-go traffic because of inexperience with the vehicles. When the employees learn how they work and how they move the efficiency increases (Ullrich, 2015 p.162-163). The employees are expected to be responsible adults that are aware of the risks with the vehicles. When the AGVs are operating in public areas or where non trained personnel is moving organizational and technical measures are required to guarantee the highest possible level of safety without greatly impacting the performance level (Ullrich, 2015 p.163).

Navigation methods that follow a physical guide path on the surface, such as passive inductive guidance and optical guidance, are not suitable if there are other vehicles operating in the same area. This is since the other vehicles will tear the markings on the floor which could result in disruptions in the AGVS's operation (Sankari and Imtiaz, 2016).

The condition of the floor where the AGV operates is of high importance, both in regard to safety and to disruption-free operations. Ullrich (2015, p.155-156) gives a number of criteria that he thinks should be met in order not to have issues with the floor.

- A high shear strength of the floor is important since the AGV drives the exact same path each time. Otherwise it will cause tracks on the floor.
- Evenness of the floor is important in order to have a high precision when conducting loading operations.
- The AGV must be able to handle uphill and downhill grade deviation without risking that the safety functions, such as the emergency brakes, do not function as required.
- It is important that the floors are cleaned regularly since contamination could affect the stopping distance of the vehicle.

As mentioned in subchapter 3.2.1 AGV Guidance Control System, the guidance control system communicates with the AGVs and the equipment that it collaborates with by a WLAN connection (Ullrich, 2015 p.123). A WLAN in an industrial environment poses several different challenges that it does not in home and enterprise environments. In an industrial environment there is a significant amount of electrical noise coming from competing radio systems, radar and microwave sources and welds (Wilamowski and Irwin, 2011). This disturbs the connection with the WLAN and can make the guidance control system lose connection with the AGVs or the peripheral equipment. The range of the access points, that distributes the WLAN, is also limited and an extensive amount of manual labour is required to install these access points (Wilamowski and Irwin, 2011).

In the article *Proving the Safety of Autonomous Systems with Formal Methods - What Can You Expect?* by Tempelmeier (2011), the importance of environmental influences is taken to an extreme. Tempelmeier (2011) means that the AGVS is based on mathematical calculations. Depending on the weight of the load the AGV can for example calculate how long the length of the brake path will be. These calculations do not cover environmental influences and can therefore never be fully relied upon under the influence of irregular external effects. An example is an oil spill that would affect the deceleration of an AGV. Tempelmeier's (2011) conclusion is that it is impossible to include all the potential external effects that the AGV depends on in the calculations. Therefore it is important that the AGV operates in a controlled environment where the employees are aware of its shortcomings and the importance of avoiding divergences in the operational area. Tempelmeier (2011, p.64) ends his article by citing Albert Einstein, "*As far as the theorems of mathematics relate to reality, they are not certain, and as far as they are certain, they do not relate to reality.*"

3.5 THE FUTURE

Technological advances in the field of AGVSs are today fast and happening in many areas. AGVSs are often based on advanced technology which leads to many areas of possible improvement. Ullrich (2015, p.165-179) has many thoughts on this subject. In his book he suggests a number of areas of development that are more or less close in time. In this subchapter a few areas considered to be relevant for this study will be mentioned.

The first topic Ullrich (2015, p.165) brings up is the development of sensor systems. This can be the developments of the hardware like mentioned in subchapter 3.2.2.2 or software development connected to the sensors. The topic brought up in subchapter 3.2.2.2 was that a development where sensors for safety and navigation could be combined could lead to cost savings. The software development could be based on information from the internet, for example face recognition. According to Ullrich (2015, p.165) Google owns hundreds of patents on this topic and this could be used in material handling operations, for example pallet recognition. If this was implemented AGVs could pick up pallets that were placed in a wrong angle or similar.

3D obstacle recognition is a topic of the future. With this an AGV could create a 3D-image with its sensors and recognize persons and objects. They could for example see crane hoops or the prongs of a raised forklift and by this offer a considerably higher level of safety. Safety sensors would not necessarily have to be mounted on the AGV but could be placed on the ceilings of passageways for example, see figure 3.22. They could there collect information about people in the corridors and transmit this wirelessly to the guidance control system. It could also allow an AGV to be aware of the traffic situation in a new passageway before turning into an intersection (Ullrich, 2015 p.171-173).

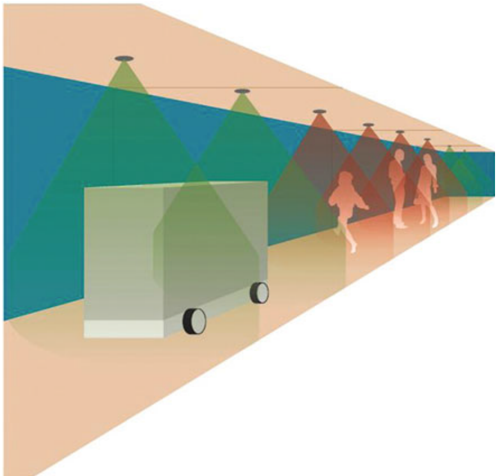

Figure 3.22 - Safety sensors placed in the ceiling (Ullrich, 2015 p.172)

Ullrich (2015) also mentions areas such as truck loading and speech guidance as future possibilities. Right now it is difficult for an AGV to load a truck and if it is possible it takes a lot more time than doing it with a manual forklift. With independent measuring of the cargo area faster and better loading could be achieved. Speech guidance could be used for quick orders from operators such as "Bring these pallets to the warehouse!", "Where are you going?" or "Wait!". For this to be possible the AGV needs to recognize the operator and his or her order must be understood (Ullrich, 2015 p.168).

Batteries and energy supply is also a topic of the future. Ullrich (2015, p.173) believes that lithium-ion is the main representative of the new battery technologies. This also leads to the area of environmental protection and sustainability. According to Ullrich (2015, p.179) more and more users are going to be placing emphasis on environmentally friendly resource-efficient intralogistics and will have a more critical view of current battery systems. This means not only considering the environmental effects of the system while in operations but also their manufacture and disposal.

For a time there has been some research into Swarm Intelligence. This refers to the sophisticated collective behaviour that can emerge from the combination of many simple individuals that operate autonomously. On their own they would not work successfully but as a collaborative unit they can achieve many things. Inspiration for this has come from monitoring social insects and animals, such as ants, bees or birds. Swarm intelligence applied to robotics is called Swarm Robotics (Mohan and Ponnambalam, 2009). Recent advances in technology make it possible to produce simple robots of reduced size and cost. Swarm robotics is an approach of coordinating these robots. They operate as a decentralised system, without a guidance control system, that communicates with each other. By working in this manner the system becomes robust since it is not affected by the failure of a single robot (Kolling et al., 2015). Since the robots are communicating they are able to warn each other and offer assistance. Swarm also has the advantage of being scalable and self-explanatory in the sense that the operator can set up the system. This technology has a limited field of application to classical AGVs but can be useful for small intelligent AGVs. These could be used for a new area of flexible "fetching and bringing" operations wherever there is not a large fixed material flow (Ullrich, 2015 p.171).

4 EMPIRICAL STUDY

This chapter describes the information gathered from interviews conducted with employees at Scania, suppliers and reference companies.

4.1 SCANIA

4.1.1 A general description of the material flow as Scania's production units

To create a general description of the material flow at Scania's production units, visits at the production units were conducted. Below is a description of the material flow at Scania. There are, in addition to this, several special flows at the different production units that have been excluded to make the description as general as possible.

The material arrives to the production unit from three different sources. Either from a logistic centre, from external suppliers or supplied internally from another production unit. At arrival forklifts place the material in buffer stocks, either in floor storages or at the platforms. The platforms, a fast-pick area, are standardised modules where picking is done in the production unit, see figure 4.1. At the platforms the material is picked in batches, kits or sequences. These three different supply methods are designed to fit the takt time and the different varieties that are produced in that takt. Batches, kits and sequences are loaded onto carts and then to a logistic train. The train is also loaded with pallets collected from the floor storages. These trains then travel in a loop around the production line to replenish certain parts. There are different trains loaded with different materials depending on the takt.

At the production line, the material is replenished in different ways. Pallets are stored at the production with a multiple-bin system where the line always has a buffer. The empty pallets at the production line are replaced with the new ones. Batches, kits and sequences are either stored at the line with a single-bin system or replenished by transferring the material by a flow rack, a procedure called shootring. The single-bin system implies a timing issue since the train has to arrive exactly when the existing bin becomes empty. If it arrives too early it will create a return flow of the material that was not used. With shootring the timing issue is avoided. The empty bins that are replaced at the production line are then loaded onto the train and transferred back to the platforms. In addition to this material flow there is a box flow that supplies both the platforms and the production line with smaller articles that are stored in boxes. Between different processes and from final assembly to finished goods storage the product is transported either by forklifts or with an automated solution like a conveyor or crane.

Figure 4.1 - An example of a platform at Scania (Source: Scania)

4.1.2 Conducted interviews with employees at Scania

4.1.2.1 Ruthger de Vries regarding Scania's forklift free strategy

Scania has a strategy to remove forklifts in its production to the greatest extent possible. This strategy is the reason why the material handling processes are organised the way they are and why logistic trains are used. To get a deeper understanding why this strategy was created an interview was conducted with Ruthger de Vries, Executive Vice President for Production and Logistics.

According to de Vries (2017) the strategy is based on two factors. Manual driven forklifts are dangerous and impose a safety risk to the personnel. The use of forklifts should therefore be minimised to increase the level of safety in the production. The other reason for the implementation of the strategy was to standardise the material flow and create a material handling process that is synchronised with the production process.

Before the forklift free strategy was implemented the material handling strategy was to minimise the number of transportations and instead increase the volume of each transportation. It was also a strategy to reduce the amount of repacking by, to the greatest extent possible, using the same load carrier as the material was delivered on, often pallets. This led to large volumes of material at the production line and made it impossible to plan the replenishment of material since there was no information regarding how much material each production station had.

The new strategy was to have a material handling process that supplied the production with material when it was needed, synchronised with the takt time and the variations of products that were produced. Instead of using the same load carriers that the material had arrived on the material was repacked according to the takt time in smaller batches. In that way the planning unit could know how much material each station had and when it needed to be replenished. The new material handling process consisted of logistic trains supplying different parts of the production according to the production plan. In this way the material handling process and the production process got more synchronised and the operational staff could control and plan its tasks and with that make it more efficient.

The use of logistic trains instead of forklifts is therefore because of two reasons; to increase the level of safety and to gain control of the process and synchronise it with the production's takt time.

4.1.2.2 Tina Arnstedt about Scania's company culture

To get an overall understanding of Scania's strategy and organisation an interview was conducted with Tina Arnstedt, Senior Manager at Global Logistics Development Scania. Many areas about the organisational structure were touched upon but the topic relevant for this study was what Arnstedt (2017) said about Scania's strategy regarding new technologies. According to her Scania has realised that a lot of problems with the implementation of new technologies can be avoided by only implementing proven technology. A lot of the initial issues with a technology have then been solved which leads to a smoother implementation for Scania. Scania prefers to use this proven technology, and normally starts with a smaller pilot to ensure the output before doing an implementation in a larger scale.

4.1.2.3 Gunnar Granqvist about IT

The importance of involving the IT-department when implementing an AGVS was something that both theory and the suppliers mentioned. The AGVS needs to be connected to the WLAN in the facility and to the internal logistics operational system. To understand what complications, connected to IT, the AGVS technology could have an interview was conducted with Gunnar Granqvist, Business Relationship Manager within the IT-department and member of the AGV competence group.

Granqvist (2017) says that the issue with the AGVS technology, connected to IT, is the connection to the WLAN. The issue with an industrial environment is that there are many aspects that disturb the connection. Things as welds that emit radiation and racks with material made of iron are factors that are present in an industrial environment and that disturb the connection. The problem is that when the network is installed it is hard to take all these environmental aspects into consideration. The welding robots are constantly moving which results in deviations in the WLAN around them.

Granqvist (2017) explains that he has been involved in projects before where devices within the production require a connection to the WLAN. An example is a project at the production unit in Oskarshamn where a device, that required a connection to the WLAN, was installed on the manual forklifts. The issue with the device was that it did not switch between different access points while the forklift was moving. This resulted in the device being connected to one access point until it had moved out of reach. It then lost its contact even if the signal was strong in the whole facility. All devices had to be reprogrammed so that they would switch to different access points while moving around in the facility. In this case it was not an AGVS but an AGV could have the same programming error (Granqvist, 2017).

Granqvist (2017) concludes with saying that the issue is not the WLAN, it is the industrial environment in which it operates. In a warehouse or other type of environment this would not be an issue since the environment is more constant and many of the aspects that are an issue in the production unit are not present.

4.1.2.4 Thomas Paulsson about safety

To understand Scania's view on safety an interview with Thomas Paulsson, Senior Advisor Safety Processes at Scania, was done. Paulsson (2017) says during the interview that manual forklifts have for many years been talked about as one of the most dangerous work equipments at Scania. If you look at accidents in the company, forklifts are well represented as causes for these. Two years ago a co-worker in Brazil was killed as the result of a forklift.

Paulsson (2017) states that in most cases an AGVS is probably safer than a system with vehicles steered by humans, but he still has some concerns. He says that in many cases when implementing a system like this a lot of focus is on how risks, from forklifts in this case, will disappear. What can however be forgotten are the new risks that can come with an AGVS like this.

New risks that Paulsson (2017) mentions are for example lack of maintenance. For a manual forklift the forklift driver does daily checks every morning and probably notices if something feels wrong during his or her shift. An AGV does not have a driver and because of this a structured system of daily maintenance has to be created to detect problems before they become too big or a safety risk.

Another risk that Paulsson (2017) sees that is directly connected to one type of AGV is the wagons behind a towing AGV. He means that if someone steps in between the wagons the AGV will not notice this and will not stop. He says that you can put safety scanners on the AGV itself but if you have five wagons and you have different wagons depending on which process the AGV is working with you cannot put sensors on every wagon. Then you just have to assume that no one will step in between the wagons. If you have a human driving the towing vehicle he or she can look back but a sensor on the AGV cannot. If the speed of the AGV is lowered the consequences of an accident like this becomes smaller. Paulsson (2017) says that in Scania's production plant in Brazil they have a towing AGV where they have made the decision that the AGVs go so slowly that the consequences of someone stepping in between the wagons will be very small. They have therefore not chosen to add any extra safety equipment on the wagons.

Another aspect that Paulsson (2017) brings up is the question about what happens if something out of the ordinary occurs in a process where an AGV works. How does the AGV handle this? This could for example be that the AGV has to lift a pallet that turns out to be broken. A human could notice this but the AGV does not. To transport a broken pallet could lead to a safety risk as it could be dropped.

4.2 Suppliers

4.2.1 Supplier description

4.2.1.1 AGVE

AGVE was founded in 1985 under the name AGV Electronics. The original business model was to develop and market electronic control components for AGVs. In 1989 AGV Electronics started developing tailored AGVs. Today they have five different business areas: Automated Guided Vehicles, Vehicle Control, AGV Systems, Robotics, and Aftermarket service and support. Because of the broader business scope they decided to change their name from AGV Electronics to AGVE in 2013 (AGVE, 2017b).

AGVE is a turnkey supplier of AGVSs with 60 employees worldwide. Their headquarters are located in Sweden and they have local offices in Germany, the USA, the UK, Italy, the Netherlands and South Korea. Since 1990 they have delivered more than 2500 AGVs, and a total of 130 unique designs (AGVE, 2017b). They produce fully automated vehicles in five different standards. The five different vehicles can be modified in different ways depending on what type of AGV that is needed. Examples of modification can be to transform the AGV into a towing vehicle, give it forklifts or conveyors. Beside these five standard vehicles AGVE also produces an underride AGV that is used in hospitals and fully customised solutions. All vehicles can be combined with any type of navigation (AGVE, 2017c; AGVE, 2017d). AGVE's solutions are thereby very flexible.

The interview with AGVE was held with Jakob Dannemark, CEO and co-owner of AGVE. The interview took place in AGVE's office in Gothenburg, Sweden.

4.2.1.2 DS-Automotion

DS-automotion develops and distributes AGVs for five different segments, Automotive, Print and Paper, Hospital and Healthcare, Agriculture and Intralogistics. The company was founded in 1984 and is now based in Austria (GmbH, 2017). DS-automotion has several different types of AGVs in their product range. They have underride AGVs both for industrial use and hospitals, assembly line AGVs, piggyback AGVs and forklift AGVs both without space for a human driver and with, then serially produced by Linde (GmbH, 2017). They use many types of navigation where the fixed path navigation methods are active and passive inductive guidance and optical guidance. The open navigation methods are magnetic spot navigation, laser navigation and contour navigation with SLAM (GmbH, 2017).

The interview with DS-automotion was held with Markus Gartner, Sales Engineer and System Designer for AGVSs. The interview took place on skype.

4.2.1.3 Egemin

Egemin designs, integrates and maintains turnkey automated material handling solutions. Egemin has three areas of expertise, automated warehouse and distribution solutions; Automated Guided Vehicle solutions and In-floor chain conveyor solutions. The company's headquarters are located in Belgium and they have local offices in: the Netherlands, France, Germany, the UK, the USA and China. Egemin was founded in 1947 and was from the beginning specialised in naval electricity repair work. It was first in 1958 that the company expanded its business to handling systems (Egemin-automation.com, 2017a). Egemin has three different segments of AGVs. The E'gv Standard is a specially designed AGV and can be a forklift, a towing or a piggyback AGV. The E'gv Hybrid is a forklift AGV that is serially produced by Linde, STILL or Baoli. The third segment is the E'gv Custom, a fully customised vehicle (Egemin-automation.com, 2017c). Egemin offers any navigation method for their AGVs (Egemin-automation.com, 2017b).

Since 2015 Egemin is part of the multinational KION Group that is one of the world market leaders in intralogistics. The KION Group consists of Linde, STILL, Baoli, Fenwick, Voltas, Dematic and Egemin. Linde, STILL, Baoli, Fenwick and Voltas manufacture industrial forklifts and Dematic and Egemin are specialised in automation (Kiongroup.com, 2017).

The interview with Egemin was held with Noë van Bergen, International Business Development Manager at Egemin. The interview took place over the phone.

4.2.1.4 Jernbro

Jernbro is a company based in Gothenburg that delivers AGVs (Jernbro. Industriservice för bättre snurr, 2017b). They have offices in 20 cities and a total of 750 employees (Jernbro företagsbroschyr, 2016). With their base as an automation company within Volvo Group they have broken off and are now an independent company (Knutsson, 2017). They have during the years delivered around 600 AGVs (Jernbro. Industriservice för bättre snurr, 2017a).

Jernbro mainly focuses on assembly AGVs but supply other types as well (Jernbro. Industriservice för bättre snurr, 2017a). They make forklift AGVs and are right now developing an underride AGV. They work with active and passive inductive guidance navigation, contour navigation and optical navigation (Knutsson, 2017).

The interview with Jernbro was held with Pär Knutsson, Project Manager Sales at Jernbro. The interview took place in Jernbro's office in Skövde, Sweden.

4.2.1.5 Softdesign

Softdesign is an AGV software company based near Gothenburg, Sweden. Softdesign has an electrical, mechanical and design partner called Atab that manufactures the hardware for the AGVs while Softdesign contributes with the software. Together they create a product called MAX AGV where the software is called MAX (Softdesign.se, 2017).

Softdesign was founded in 1987 (Softdesign.se, 2017) and now have 17 employees (Allabolag.se, 2017b). Atab was founded in 1973 (Atab.se, 2017) with a current number of 16 employees (Allabolag.se, 2017a). They have collaborated for many years now and deliver a range of AGVs. The AGVs they supply are forklift AGVs without space for a human and piggyback AGVs (Maxagv.com, 2016c). The AGVs use laser navigation.

The interview with Softdesign was held with Christopher Wessberg, Deputy Managing Director at Softdesign. The interview took place in Softdesign's office in Gothenburg, Sweden.

4.2.1.6 Toyota Material Handling

Toyota Material Handling Sweden (TMHSE) is Sweden's largest supplier of forklifts. The company has 460 employees where around 270 are a part of the service and maintenance organisation in Sweden. TMHSE is a part of Toyota Material Handling Europe (TMHE) which is a part of Toyota Material Handling Group. TMHE has production centres in Mjölby, Annecy in France and Bologna in Italy (Toyota-forklifts.se, 2017).

Toyota Material Handling sold their first forklift in 1956 (Global-toyotaforklifts.com, 2017) and started selling automated vehicles in 2009. They deliver two types of AGVs, automated warehouse trucks (forklift AGVs with space for a human) and automated carts (underride AGVs). The warehouse trucks navigate with laser and the automated carts with magnetic tape (Toyota-forklifts.eu, 2017a). According to Eriksson (2017a) contour navigation is under development for the warehouse trucks and will be available in the spring of 2017.

The interview about Toyota Material Handling was held with Henrik Eriksson, Business Development Manager with focus on automation at Toyota Material Handling. The interview took place in Toyota Material Handling's office in Gothenburg, Sweden.

4.2.2 Compilation of supplier interviews

4.2.2.1 AGV types

Categorising AGVs

Since there is no official nomenclature for how to name different types of AGVs suppliers use varying names. Toyota Material Handling has for example divided the different types as illustrated in figure 4.2. They call forklift AGVs without space for a human AGVs, and with space for a human AGFs (Automated Guided Forklifts). Underride AGVs are divided into two groups, AGCs (Automated Guided Carts) and AMRs (Autonomous Mobile Robotics). AGCs are simple vehicles that are easy to install yourself. AMRs are more complex AGVSs and according to Eriksson (2017a) a completely different segment, not very often used in industrial environments.

Egemin have chosen different names as they call their forklifts without space for a human Standard AGVs and with space for a human Hybrid AGVs (Egemin-automation.com, 2016c). AGVE has chosen the same names (Dannemark, 2017b).

DS-automotion divides their AGVs into two categories, assembly line AGVs and intralogistic AGVs. For an assembly line AGV the vehicle has to be adapted to the item it is carrying, to the ergonomically best position for the employees and other factors like this. The technology is always more or less the same but the outside is adapted to the product. Intralogistic AGVs are completely different. Here you use the AGV to supply material to the line and this can in turn be divided into subcategories like underride AGVs, forklift vehicles, towing AGVs etcetera (Gartner, 2017).

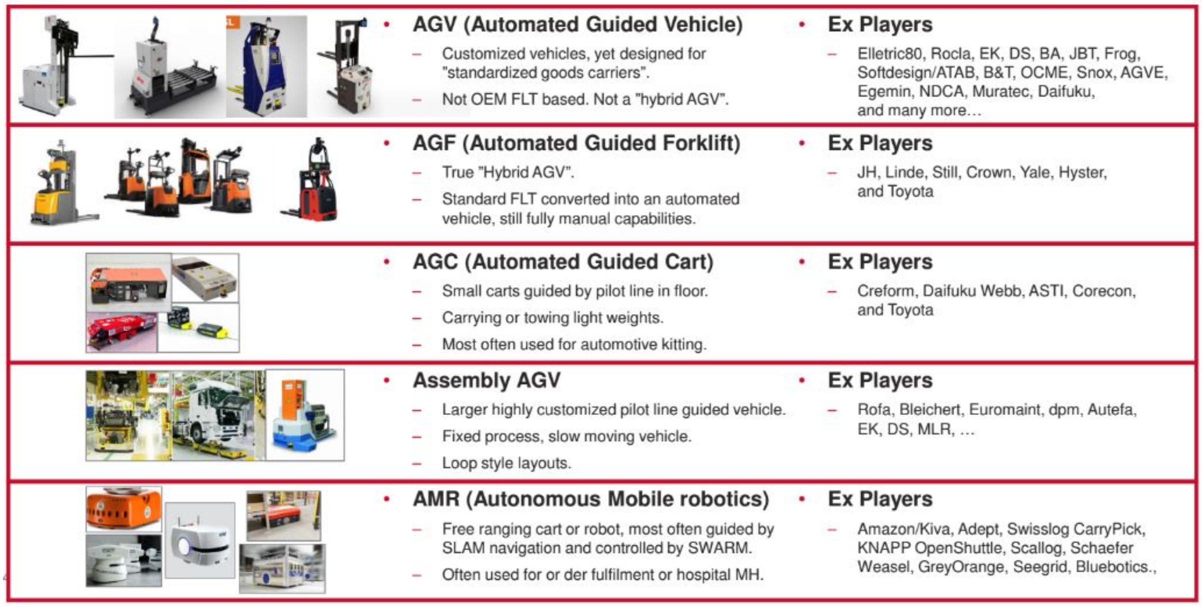

Figure 4.2 - Toyota Material Handling's categorisation of AGV types (Toyota, 2017b)

Forklift AGVs with or without space for a human

When it comes to forklift AGVs, the suppliers have two different ways to go. Either you can have a forklift AGV with space for a human to drive it manually or without space for a human. Most interviewed suppliers have a strong belief of which type that is the best one for standard operations.

Eriksson (2017a) and van Bergen (2017) think that forklift AGVs with space for a human are the way to go. Eriksson (2017a) says that these have a big advantage when service or maintenance is to be executed as the driver can simply step into the AGV and drive it to the maintenance area. In these cases the switch between the manual mode and the automated mode is very smooth. He also says that a forklift AGV with space for a human gives a feeling of safety to the customer because a manual forklift is something they recognize. He does however also mention that this is a pseudo argument because if you have to drive an AGV manually you have not succeeded in the implementation of the system. According to Eriksson (2017a) forklift AGVs without space for a human are good for obscure applications when one wants to transport high weight loads, work in special environments or with special operations. A forklift AGV with space for a human cannot be made to handle these situations.

Van Bergen (2017) at Egemin has the same opinion as Eriksson (2017a) in preferring forklift AGVs with space for a human. He mentions, just as Eriksson (2017a) did, the psychological advantage that comes with a forklift AGV with space for a human as these AGVs are similar to the old manual forklifts. This makes the change seem smaller. Van Bergen (2017) also brings up the advantage that a forklift AGV with space for a human means less change in the processes as the AGVs can still be used manually for some activities.

Dannemark (2017b) does not agree with this argument. He says that AGVE makes forklift AGVs with space for a human if the customer wants to have this but they do not recommend it. He states that it is a very bad idea to drive an AGV manually and says that he guarantees that if you drive an AGV in the manual mode you will break something on it in the end. It sounds smart to be able to use it manually but as an AGV has so many expensive parts built onto it the economic risk becomes higher. Dannemark (2017b) means that when you put an AGV in manual mode all safety sensors are turned off and you can hit anything. If you look at a manual forklift it is quite dented, you do not want those kind of damages to an AGV. He also points out that the sensors are put in positions that are exposed so that they are able to see. If you brake a safety sensor a new one costs 30 000-40 000 SEK and a navigation laser 70 000 SEK. According to Dannemark (2017b) it is better to buy an old used manual forklift and put it in a corner and use this one instead of the AGV in situations when a manual forklift is needed. The cost for the spare parts for an AGVs used in manual mode will soon add up and become higher than the cost of an extra manual forklift.

Gartner (2017) at DS-automotion does not have an as strong opinion in the matter as the other suppliers do. He simply states that in 80-90 per cent of the cases forklift AGVs with space for a human are used. There are some specific situations, like if you have limited space, where you cannot use these and then you have to make a forklift AGV without space for a human. He does however, just as van Bergen (2017) and Eriksson (2017a) also state, that there is a cost advantage with a forklift AGV with space for a human since the forklift is built in a serial production with higher volumes. Gartner (2017) points out that there is a higher engineering cost when buying forklift AGVs without space for a human. This does however depend on the number of AGVs that are in the system according to him, if you buy more AGVs the engineering cost can be split on a higher number of vehicles.

Dannemark (2017b) says that the higher cost of an AGV without space for a human is true in theory but that AGVE has solved this by building their AGVs in a serial production as well. This is done at Actil[13]. They build AGVE's AGVs on the same line as their own forklifts. The AGV is based on Actil's forklifts but the automation is added and the space for the human removed. By this AGVE's forklift AGV without space for a human are not more expensive than a forklift AGV with space for a human.

Outdoor AGVs

When asked about the possibility of outdoor AGVs most suppliers said that this is not something they supply. AGVE is the exception here. They do according to Dannemark (2017b) build outdoor AGVs if the customer wishes. The AGV is then a customized AGV and can for example look like the one in figure 4.3, an outdoor AGV that AGVE has built for a company in Germany. To get an outdoor AGV to work properly there are a couple of factors that need to be considered.

It is, according to Dannemark (2017b), preferred to have a concrete floor where the AGV moves. You could put the AGV on normal asphalt roads but in the end you will have marks in the floor since the wheels are always rolling on exactly the same tracks. He says that technically it would be possible to produce rubber wheels and then it would be possible to use the AGV on asphalt. This is however not something used on normal AGVs. The normal ones have small, hard wheels that make deep marks in the asphalt quickly. If you have a bigger vehicle it might be worth it to produce an AGV with rubber wheels since the small wheels will not be enough (Dannemark, 2017b).

When it comes to navigation, laser navigation or other methods where laser scanners are used are not appropriate because of the sunlight. The best alternative is according to Dannemark (2017b) to use an inductive guidance wire in the ground. Another alternative is to bury a magnetic tape or strip. If there is a lot of other heavy traffic where the AGV drives, a normal inductive guidance wire might

[13] Actil is a company near Linköping that develops and produces electric indoor warehouse trucks. Special trucks comprise about 25 % of their production (Actil.se, 2017).

break if a crack in the ground is created. In this case a magnetic tape in the ground is better as it will still be magnetic if it breaks.

Dannemark (2017b) also points out that the safety technology is not the same for outdoor AGVs as for indoor AGVs. Just like with navigation a safety laser sensor cannot be used because of the sun and the weather conditions. Legally it is not possible to use the same safety technology with ultra-sensors as autonomous cars do, but instead mechanical safety bumpers that hit an object physically have to be used, see figure 4.3. The bumper is soft and does not inflict damage if it hits a person and in case of impact the AGV stops immediately. Because of the mechanical bumpers the AGV cannot move as fast as one would like sometimes. The bumper has to be large enough to be able to stop in time if it hits something, even if it is fully loaded. If the AGV drives with high speed the bumper would become unreasonably big. You can drive a couple of m/s but then you start having problems (Dannemark, 2017b).

Another factor to consider is that it might be a good idea to put heating coils in the wheels to melt the ice on the driving path during winter. An icy path can also be solved by using large rubber wheels that are made for winter conditions (Dannemark, 2017b).

In general it is not that expensive to build an outdoor AGV according to Dannemark (2017b) and AGVE has done it a couple of times before.

Figure 4.3 - An outdoor AGV at a company in Germany, built by AGVE (Dannemark, 2017a)

4.2.2.2 The AGV guidance control system

The guidance control system works similar for all suppliers. The main task of the guidance control system is to enable communication between the vehicles, the internal logistics operating system and the peripheral equipment such as doors, conveyors or scanners. Eriksson (2017b) illustrates how Toyota Material Handling performs this task in figure 4.4. The two boxes in the middle with the titles "Toyota Order Manager" and "Autopilot System Manager" are the two functions that make up the guidance control system. Communication and cooperation between the different units are possible through a WLAN connection. This is generally how most systems work for the different suppliers. Some suppliers have more advanced solutions where the guidance control system also can act as the warehouse management system. This is the case for both AGVE and Softdesign (Dannemark, 2017; Wessberg, 2017). A guidance control system is always needed when the vehicles have to communicate with each other or their environment. This means that a simple system with a single AGV and simple tasks does not need a guidance control system (Eriksson, 2017a).

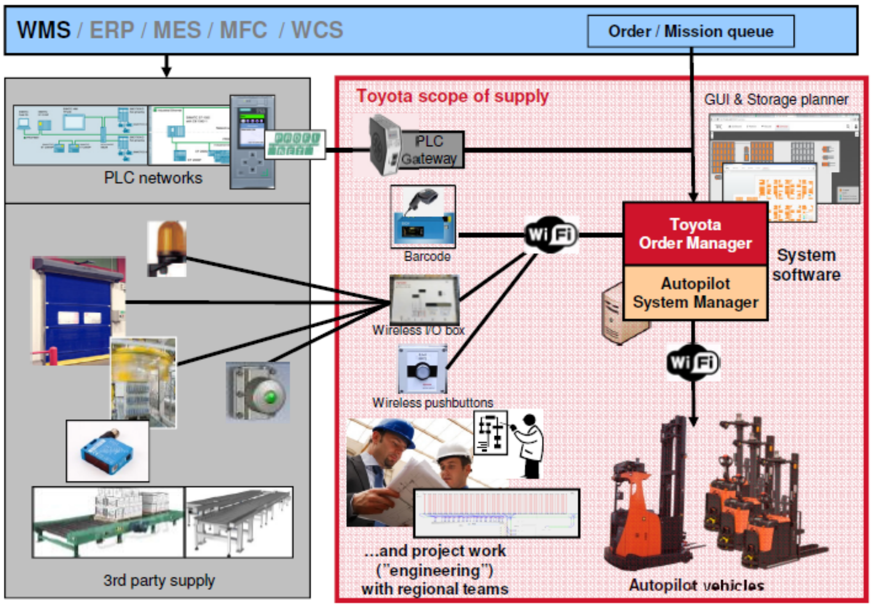

Figure 4.4 - Toyota Material Handling's illustration of their guidance control system (Eriksson, 2017b)

During the interview with Knutsson (2017) he explained the importance of a well-functioning WLAN connection. Without this the vehicle will come to a stop at locations where it has to communicate with the guidance control system. The quality of the connection is therefore crucial for achieving a well performing system. Because of the importance of a good connection many suppliers want to set up their own WLAN in the facility. This is important for the supplier as they want to be able to know if a problem in the system is caused by their system or if it is the customer's WLAN that is failing (Knutsson, 2017). Knutsson (2017) explains that this was the case when they implemented an AGVS at Volvo. In the beginning of the project the system had regular breakdowns caused by the WLAN connection. The system was then using the WLAN that Volvo already had in their facility. After investigating the issue they came to the conclusion that the breakdowns were caused by the regular updates of Volvo's own computer systems and that this overloaded the network. Because of this Jernbro decided to install their own WLAN which solved the issue. Even if many suppliers want to set up their own network it is not a necessity for implementing an AGVS, it is merely a way for the suppliers to have full control of the end result (Knutsson, 2017).

None of the interviewed suppliers' systems are able to collaborate with other suppliers' systems. For most suppliers the guidance control system is merely able to do a "handshake" procedure, which means that at locations where the systems cross each other a signal can be sent between the systems telling the other system if it is clear to pass or not (Gartner, 2017).

Since an AGVS is highly dependent on the guidance control system one can mitigate the risk of a malfunction by not having one guidance control system for all AGVs in a facility. The operations that are similar and interfere with each other should have the same guidance control system. If this is not the case it is better to have separate systems. The guidance control system is a small fraction of the final cost of the system so an additional system will not increase the investment drastically (Eriksson, 2017a).

4.2.2.3 Navigation methods

All suppliers have different viewpoints on the different navigation methods. Almost all of them do however agree that artificial laser navigation is best suited for most applications. Eriksson (2017a) from Toyota Material Handling argues that artificial laser navigation is the only valid method to use since it provides the best precision, performance and with that enables the highest possible driving speed. The fact that artificial laser navigation has the best precision compared to different navigation methods is something that both van Bergen (2017), Wessberg (2017) and Gartner (2017) agrees on. Van Bergen (2017) also mentions that artificial laser navigation is the most cost efficient method. Dannemark (2017b) does not want to explicitly say that artificial laser navigation is the best method even if it, according to him, is the method that is most often used. He says that it depends on the task and the situation and that you should not be locked in on one alternative.

Knutsson (2017) from Jernbro is of a different opinion. From his experience with artificial laser navigation there are many factors speaking against this type of navigation. The installation time for the reflectors is longer than installing other methods and with a dynamic production area there are other alternatives that are better. He also mentions that the reflectors are sensitive and can fall down if hit by manually driven forklifts. When asked about what happens if reflectors fall down Eriksson (2017a) has a different opinion, "first off the reflectors do not fall down, and if they would it would not affect the performance since there are normally up to ten visible reflectors that can compensate for it." (Eriksson, 2017a). Regarding the installation time of the reflectors Eriksson (2017a) says that it takes approximately fifteen minutes per reflector and when the reflectors are installed you can easily change the paths in the computer as long as at least three reflectors are visible.

When it comes to other navigation methods the opinions differ between the different companies. According to Gartner (2017) fixed-path navigation is only suited for assembly line AGVs since they do not require the same level of flexibility as AGVs for intralogistic operations. Dannemark (2017b) thinks that this strict viewpoint on the different methods limits the solutions too much and that as a supplier you have to be flexible and adaptable to the customer's demands. He says that all methods can have the same precision by adding extra markings or location spots where higher precision is needed. High precision is not always a necessity for all operations. According to Knutsson (2017) it might be more cost efficient with a less advanced navigation method, such as optical guidance, for simple tasks.

The choice of navigation method also depends on what type of AGV that is used. Artificial laser navigation requires that the laser scanner is put on top of the AGV in order to find the reflectors. For underride AGVs the scanner cannot be placed in a good spot and that is why it is not suitable for that type, contour navigation is then a better choice (Dannemark, 2017b).

Contour navigation is a method that most suppliers mentions as the upcoming method. DS-Automotion, Toyota Material Handling, Egemin and AGVE offer this technology today but point out that it is not as well tested as artificial laser navigation. The advantages with contour navigation is that reflectors are not needed. DS-Automotion has also enabled the navigation scanner to be used as a security scanner as well. This makes the system cheaper since the scanners are an expansive part of the AGV (Gartner, 2017). The lack of reflectors makes the system both more robust and cheaper (Dannemark, 2017b). The issue with the technology is that it requires the operational environment to stay constant to a certain degree. According to Gartner (2017) 50 per cent of the environment has to be constant. According to Dannemark (2017b) this number is as low as 30 - 40 per cent. Contour navigation does not have the same precision as artificial laser navigation (Eriksson, 2017a). That is why many suppliers offer hybrid navigation methods where contour navigation is the main method and reflectors are placed at the locations where higher precision is required (Eriksson, 2017a). AGVE also offers this type of hybrid navigation method as well as contour navigation combined with magnet spot navigation (Dannemark, 2017b).

According to Eriksson (2017a) artificial laser navigation and contour navigation cost approximately the same but are, compared to other navigation methods, significantly more expensive. Since laser navigation allows for higher driving speed the system can however still be more cost efficient (Eriksson, 2017a).

When deciding what navigation method to use the performance and the throughput of the operation is essential (Eriksson, 2017a). Environmental aspects also have to be considered since these might restrict the use of certain methods (Dannemark, 2017b). The environmental aspects that by the suppliers are considered important are presented in subchapter 4.2.2.7.

4.2.2.4 Obstacle avoidance

When it comes to obstacle avoidance all suppliers agree that it is an unnecessary function that solves a problem that should not be there in the first place (Eriksson, 2017a; Dannemark, 2017; Knutsson, 2017; van Bergen, 2017). A production area should be as clean and tidy as possible and you do not want an obstacle lying in the way even if you do not have an AGVS (Eriksson, 2017a). If a manual forklift or an AGV has to stop in front of an AGV because it has to perform a task the AGV can be programmed for this in advance and have alternative paths to drive along (Dannemark, 2017b).

4.2.2.5 Safety

When it comes to safety, there is no doubt among the interviewed suppliers that it is an important topic. Increased level of safety is considered to be one of the main advantages when implementing AGVSs (Wessberg, 2017) but what safety aspects that the suppliers feel are mandatory and suitable when selling an AGVS vary slightly.

The EN 1525

All interviewed suppliers mention the EN 1525 as an important regulation. Some look at the areas included in the regulation as the bare minimum and that an AGV preferably should have more safety features than stated in the regulation. Others see the regulation as a strong recommendation that can be discussed if needed. Knutsson (2017) is of the opinion that the EN 1525 is not enough and that some suppliers are bad at following the standard which is not good. He means that it is an old regulation and that it has some major flaws. An example is that the wagons connected to a towing AGV do not have any safety equipment which means that the AGV does not react if someone is standing between the wagons (Knutsson, 2017). Jernbro has therefore chosen not to offer towing AGVs and to add more safety as Knutsson (2017) means that their customers, such as Volvo Cars, have high standards and demand a higher level of security. For example they have a three-position device when disconnecting the safety system to drive the AGV manually. As far as Knutsson (2017) knows no other supplier has this high security when it comes to driving the AGVs manually. Van Bergen (2017) states that Egemin follows the EN 1525 but that they can add more safety equipment if the customer requests this. Softdesign has a similar method of working as they follow the EN 1525 but adapt according to the nature of the project (Wessberg, 2017). Dannemark (2017b) says that AGVE follows EN 1525 and that the regulation works well.

Eriksson (2017a) sees the EN 1525 as a very strong recommendation. He means that sometimes you can disregard the EN 1525 on some points if you compensate with other safety procedures. He gives the example that in the EN 1525 it says that there needs to be 500 mm between a permanent object and an AGV. If this is not possible to achieve one can choose to let the AGV drive closer to the wall to create a safer environment overall in the material handling process. One could also let the AGV drive closer to the wall in a passage where it might not be possible to have an AGV, but then let the AGV blink, do sounds and slow down to make the passage as safe as it would have been if it was wider.

He does however add that the AGVs of course are manufactured to comply with the EN 1525 and a range of other regulations for electricity and so on. An AGV complies with the same regulations as a normal forklift but with the EN 1525 added. Eriksson (2017a) thinks that the EN 1525 works well as a guideline but that an additional part in the regulation should be added about risk assessments. He means that it should be compulsory for the customer to do their own individual risk assessment as an AGV supplier can make a safe AGVS but can never control what the customer will actually put on it or use it for in the end.

DS-automotion does, just as Toyota Material Handling, see the EN 1525 as a strong recommendation. Gartner (2017) says that the main point of the regulation is the minimum distance from the AGV to the walls or solid points in the environments. DS-automotion simulates the planned operation of a project and at any location where the EN 1525 cannot be followed they find alternative solutions and discuss it with the customer. Gartner (2017) says that DS-automotion is flexible in order to make the system as optimal as possible.

How safe is an AGV?

There seems to be no question regarding the fact that an AGV is safer than a manual forklift. Dannemark (2017b) says that many companies want to remove manual forklifts. This is according to him because forklifts are the biggest reason for injuries and deaths at companies that use forklifts. He claims that it is standalone the most dangerous product that exists in production and warehousing. AGVs have an exceptionally few amount of human injuries, AGVE has in 30 years not had a serious human injury.

When asked what kind of injuries that have occurred Dannemark (2017b) mentions the most serious one he knows about. It was an accident that happened in connection to an AGV made by a European supplier. He recounts an incident where a person was putting products on a pallet and then gave a signal to the AGV that the pallet was fully loaded. The person in question then went up to the AGV to correct something on the pallet when the AGV started reversing. There are two photocells on the prongs that are there to stop the AGV if it hits a rack or something alike, it is not a safety feature for humans. The person in question happened to have shoes in a material that the photocells did not detect and because of this the AGV did not stop reversing. A safety sensor would have detected this but since the photocells are not made for this type of detection they did not alert the AGV. The AGV hit the person's foot and kept trying to reverse which means that it kept pressing the foot. He or she fell and accidentally hit the flap that detects when the AGV has reached all the way under a pallet when picking it up. Since the person hit this flap the AGV luckily stopped. The person broke his or her leg but if it had not stopped because of the flap he or she might have died. The photocells will stop the AGV in many cases but not all as it is not built for this. He means that one should stay away in loading situations because there is a jamming risk, and that some common sense helps a lot. He adds that when the AGV is driving in a corridor the risk of something happening is however very low.

When asked a follow up question regarding why there is no safety equipment in the prongs Dannemark (2017b) answers that the regulations state that if the AGV is programmed to only reverse very slowly, 0.3 m/s, no safety equipment is considered needed in that direction as it is assessed that the AGV moves so slowly that people have time to react and move or hit the stop button. If the AGV reverses faster than 0.3 m/s a safety scanner in that direction is needed. When the AGV is loading some of this safety equipment needs to be turned off as it would not be able to load or unload with it on.

Technical safety features

All suppliers use laser safety sensors for their AGVs. During the interview with Eriksson (2017a) he mentions that Toyota Material Handling would also be interested in a 3D obstacle detection function if possible. This is something that you put high up that "looks" in front of the AGV and can be used for both safety and load detection. This is today a 2D curtain and Toyota Material Handling would like this feature in 3D.

Except for the safety scanners AGVE has an additional mechanical safety bumper on their AGVs (Dannemark, 2017b). Softdesign have these types of safety bumpers on the sides and on the back of the AGV that help switch off the AGV in the event of impact with an object (Maxagv.com, 2016b).

Environmental safety features

Some additional safety features and implementations that were mentioned by the suppliers are for example to add traffic lights or horizontal bars in intersections (Knutsson, 2017). Wessberg (2017), among others, mentions that light and sound can be added so that people know when an AGV is approaching. Knutsson (2017) points out that it is generally good to educate the employees on how the AGV will act and how it works. This increases safety but also productivity as the employees will not be in the way for the AGV.

4.2.2.6 Energy supply and aspects

Batteries

The types of batteries used by the different companies differ to a certain extent. AGVE uses what Dannemark (2017b) calls "all types of batteries". He says that the cheapest and most commonly used battery is traditional lead-acid ones. Lead gel batteries have according to him the same qualities but are used in environments where battery gases are considered particularly dangerous. For some situations AGVE also uses nickel-cadmium batteries but this is tried to be avoided because of strict environmental legislation. The newest technology is different types of lithium batteries. These have historically been very expensive but prices have fallen rapidly and they are now much more affordable (Dannemark, 2017b).

Toyota Material Handling uses lead-acid, lead gel and lithium-ion batteries. Lead-acid are the cheapest kind of the three, lead gel more expensive and lithium-ion the most expensive. The price for lithium-ion batteries is however decreasing and according to Eriksson (2017a) they are already today the most profitable battery if looking at a four year perspective. He means that if looking at an overall return on investment (ROI) calculation the lithium-ion battery is the best business case but if you want a good ROI for the next 18 months a lithium-ion battery might be hard to defend. Lead gel and lithium-ion batteries are relatively maintenance free and can be used in environments where charging gases are dangerous (Eriksson, 2017a). Nickel-cadmium batteries belong according to Eriksson (2017a) to the old technologies and are not good from an environmental perspective. If considering the environment lithium-ion batteries are the best.

Softdesign mostly uses traditional lead-acid batteries. It is according to Wessberg (2017) a robust technology and it works well in counterbalance forklifts since it weighs a lot. Lead gel is also used sometimes as well as lithium-ion, it all depends on the project. Since lithium-ion is a newer technology more surveillance is needed as well as more engineering hours when implementing it. There is a risk of explosion with these batteries and this needs to be controlled. Softdesign generally looks at the factors; price, function and environmental impact when recommending a battery type to a customer (Wessberg, 2017).

Jernbro is the company that highlighted the question of choosing the right battery and charging technique the most compared to the other interviewed suppliers. During the interview with Knutsson (2017) he talked a lot about how important it is that the “energy balance” of an AGVS is well calibrated. Jernbro uses lead-acid, lead gel and lithium-ion batteries. Knutsson (2017) mentions similar advantages and disadvantages with the different battery types as the other suppliers. He does however point out that it is often smart to choose lithium-ion batteries. Because of the automotive industry a lot of research has been put into this kind of batteries and in a couple of years the problems with them, such as the risk of the battery catching fire or exploding, will be solved.

Egemin uses lead-acid, lead gel and lithium-ion batteries. Van Bergen (2017) says that lead-acid is the most common one since it is cheap and it works well. The demand is however increasing for lead gel and lithium-ion since they charge fast and are maintenance free.

DS-automotion uses lead-acid, lead gel, nickel-cadmium and lithium-ion batteries in the majority of their projects. According to Gartner (2017) the battery depends on the type of operation and how many shifts you have. He points out that lead-acid batteries create charging gases which can be dangerous. Nickel-cadmium batteries can create charging gases as well which is why the demand for nickel is decreasing and more suppliers are going towards lithium-ion. The lithium-ion batteries also come with risks depending on what type of lithium-ion battery you are using, it is therefore important to choose a type that comes with less risk (Gartner, 2017). In general Gartner (2017) thinks that the industry is going towards lithium-ion batteries. They are still quite expensive but prices are falling and will fall even more. He points out that these are especially good in a situation where a company uses opportunity charging and three shifts, for one shift operations a lithium-ion battery does not make sense from a commercial perspective.

Charging

There are a couple of methods to choose from when it comes to charging and these are more or less suitable for different battery types.

Jernbro uses different charging schemes based on what goes best with the system’s “energy balance”. They offer manual and automatic battery swapping. They also offer hybrid-induction charging which means that the AGV is charged wirelessly while it is moving on certain paths. This is a method that is about a tenth as fast at charging the AGV as a normal charging method which makes it less attractive. Except for these methods Jernbro also uses stations for opportunity charging as well as on-board chargers. An on-board charger is a cable that is installed on the vehicle and that can be plugged in in a normal electricity socket (Knutsson, 2017). For a system with two shifts, Knutsson (2017) mentions that he might recommend a lead gel battery that is large enough (around 300 A) to make it through two shifts and to let it charge during the night.

Egemin uses manual or automatic battery swapping or opportunity charging (van Bergen, 2017).

Toyota Material Handling uses opportunity charging for lead gel and lithium-ion batteries and battery swapping, either manual or automatic, for lead-acid batteries. When using opportunity charging with lead gel batteries the minimum possible charging time of the battery is made longer than for a lithium-ion batteries as a lead gel battery would otherwise be ruined faster (Eriksson, 2017a). When it comes to battery swapping Eriksson (2017a) points out that automatic battery swapping is a good technique but that it is expensive. He appreciates that an automatic swapping station costs around 100 000-300 000 SEK depending on how many batteries that need to be changed. If the customer only has one shift in the production an automatic swapping station will, according to Eriksson (2017a), probably not pay off which means that manual swapping is better.

This can for some customers be a problem as they reason that "Now that we have decided to use AGVs we want an as autonomous process as possible." They do not want to think about changing batteries and because of this many choose lead gel or lithium-ion. If the customer does not have more than two shifts for example another solution is to choose a large lead-acid battery that can last for 16 hours or so, making it through the shifts and being possible to charge during the night (Eriksson, 2017a).

Based on what Eriksson (2017a) has seen, most customers nowadays go towards lithium-ion batteries. Lithium-ion is the most environmental friendly battery which he points out is also a plus. It takes around 10 per cent of the time a battery is used to charge it to the same level again which is very fast. The same number for lead gel is 20 per cent and 50 per cent for lead-acid (Eriksson, 2017a).

Besides choosing a charging scheme based on a battery, and a battery based on how the AGV will be used, Eriksson (2017a) also points out another factor. Even if a lead-acid battery with a battery swap method is the best choice in a situation, the problem of how to solve the swap logistically still exists. The battery swap, and the charging of these batteries, has to be done at a secure location where possible charging gases can be handled. This might force the AGV to leave its operating space and predetermined path. Because of this a battery that can handle opportunity charging might be a better choice as an opportunity charging station can be installed close to the AGVs' operating area.

Dannemark (2017b) at AGVE means that the cheapest charging alternative when it comes to AGVs is manual battery swapping. AGVE does however also offer opportunity charging systems and automatic battery swap where one AGV changes the battery of another. Dannemark (2017b) also mentions that AGVE do special solutions as well. If the allowed size of the AGV is limited a large battery might not fit for example. In this case a small battery with high energy density needs to be used and a charging technique chosen based on this battery. Dannemark (2017b) says that you always want to match the charging scheme to how many charging cycles a battery can handle until it malfunctions. He points out that it is easy to deliver an AGVS that functions for three months, but that is not their job.

DS-automotion mostly do projects with opportunity charging and automatic charging. Gartner (2017) says that customers normally want a fully automated system when they implement an AGVS and that they therefore do not want manual battery swapping. Another alternative is inductive charging but this is according to Gartner (2017) quite limited as it requires additional space and the charging speed is comparably low.

Softdesign uses opportunity charging to a large extent, this does however depend on the project. Projects with a manual battery swap have also been sold and if a customer only uses the AGVs during the day a scheme where they are charged during the night can be used (Wessberg, 2017).

Energy results

Implementing AGVs instead of manual forklifts comes with the advantage of lower energy consumption and with this an increased environmental friendliness. Several suppliers mention that since an AGV drives more efficiently and smoother than a human forklift driver, that is breaking and accelerating unnecessarily often, they consume less energy (Dannemark, 2017; van Bergen, 2017; Wessberg, 2017). Van Bergen (2017) points out that an AGV does have more technology on it which use electricity but that this amount is negligible compared to the saved energy from the smoother driving.

4.2.2.7 Environmental aspects

The external factors that affect an AGVS the most are according to many suppliers dirt, sunlight and heat. Dirt mainly affects the choice of navigation system. Navigation systems that rely on physical infrastructure such as the reflectors for artificial laser navigation, magnetic tape or optical lines are sensitive to dirty environments. Artificial laser navigation depends on the reflection from the reflectors and if the reflectors get dirty the AGV will not be able to determine its location in the facility. Optical navigation measures the contrast between the painted line and the floor. Dirt can interfere with this contrast and hence make the method less rigorous (Dannemark, 2017; Knutsson, 2017).

Another environmental factor is sunlight that affects both laser and optical navigation as well as the safety scanners. Since the sunlight disturbs the laser scanners both for navigation and safety this factor is extra important. Dannemark (2017b) points out that because of the low standing sun in Scandinavia this is a common problem. It can however be solved by putting a protective film on the windows (Dannemark, 2017b). Optical navigation is also sensitive to sunlight as well as other factors that disturb the contrast between the coloured line and the floor (Knutsson, 2017).

The physical environmental aspects that most suppliers mention are the quality of the floor and if manual forklifts or people operate in the same area as the AGV. This affects the performance and the precision of the system.

Since the AGV always follows the same track the quality of the floor is important because of the high amount of tearing from the vehicles. The floor has to be made out of concrete to withstand the pressure from the small wheels of the vehicle (Dannemark, 2017b). It is also important that the floors are even. Uneven floors will lead to heavy vibrations that will damage the sensitive and expensive equipment on the vehicle (Dannemark, 2017b). It will also make the AGV unsteady, especially when doing high lifting (van Bergen, 2017). If the floor is damaged with holes or large cracks the AGV can get stuck (Wessberg, 2017). Gartner (2017) also mentions the importance of keeping the floors dry since any slippage will lead to errors in the safety equipment, making the precalculated stopping distance longer than expected.

People and manual forklifts affect the AGVs performance and make some navigation methods inefficient. Navigation methods that depend on physical guide paths, such as magnetic guidance and optical guidance, risks being disrupted when the tape or colour gets teared because of crossing traffic (Knutsson, 2017). The overall performance of the AGVS is lowered since people and traffic lead to more interference with the process which leads to the AGV making unnecessary stops or drive slower (Dannemark, 2017b). Most suppliers agree that AGVs and interfering traffic from people or manual forklifts should be separated as much as possible (van Bergen, 2017; Dannemark, 2017). To solve this issue a number of things can be done. To separate the different vehicles stoplights or horizontal bars can be used and the personnel should be educated, as mentioned in subchapter 4.2.2.5 (Knutsson, 2017).

4.2.2.8 Operational aspects

Operational aspects are factors that are decisive for knowing if an AGVS is applicable for a process.

When asked what factors they think are most important when deciding if an AGVS is suitable for a process or not the suppliers' answers corresponded well with each other. The factors that are decisive can be divided into three different groups, process specific, product specific and financial specific.

Process specific factors are important to know for several reasons. Knutsson (2017) from Jernbro said that the customer must have a good understanding of their processes. If the customer does not know the details of the process it can directly be discarded, as the risk of failure in the implementation is too high. Does the customer know exactly how many transports that are done each hour and how many employees that perform these tasks today? If this information is not correct the whole system will be designed for the wrong throughput and either not be fully utilised or not have enough capacity. This was an issue that Eriksson (2017a) also mentioned where a former customer had stated that they had a certain throughput but when the system was implemented it turned out to be less than stated. This resulted in a lower utilization rate than planned and the expected result was not accomplished. To know if the customer has enough knowledge about their process some questions need to be answered. Is the process clearly defined, such as "the material is moved from one location to another", or is it complicated with many different tasks and variations in the process? (Dannemark, 2017; Knutsson, 2017). Can a transport order be generated automatically either by a sensor recognising a demand, a human triggering a demand by pushing a button or by the internal logistic system? (Eriksson, 2017). And, as mentioned earlier, what is the throughput of the process? (Eriksson, 2017, Dannemark, 2017; Knutsson, 2017).

Product specific factors tell the supplier if an AGV is able to handle the material in an efficient way. This is also a way of knowing if the customer has control of its process since it must know all the details of the products within the process (Knutsson, 2017). The product should be as standardised as possible to simplify the handling of it (Wessberg, 2017). What does the product look like, geometrically, and are there many different varieties of each product? This question is asked in order to know if the product can be handled automatically in an efficient way or if it requires a specially designed solution (Knutsson, 2017). Is the load carrier standardised or are there many different varieties? (Knutsson, 2017; Wessberg, 2017).

The last aspect is the financial specific factors. This was the aspect that Dannemark (2017b) stressed the most. Will the automation actually lead to a rationalisation and with that cut costs? Dannemark (2017b) says that there are many automation projects where the business case is not based on the number of employees that actually can be relocated, instead they are based on the number of hours a task is performed. Even if the task requires several hours the employee might still be performing another task that he or she still will be required to do if an AGV is implemented. As long as the same amount of employees are required in a process the AGVS will only lead to increased costs. To identify the processes that have the highest financial potential for implementing an AGVS there are a number of factors to analyse. The most important factor to look at is the volume of the material flow (Knutsson, 2017; Dannemark, 2017). In order to know the potential savings it is important to know the amount of employees performing the task today and how many of these that can be relocated because of an automatization. Except for rationalisation there are other factors that can lead to cost savings. Handling costs, for example from damaged infrastructure or goods, caused by manual forklifts can be an important factor (Eriksson, 2017; Dannemark, 2017). Dannemark (2017b) mentions an example when they implemented an AGVS at a company that produced and distributed televisions. The screens were so fragile that the transport with a manual forklift led to high costs related to quality issues and damaged goods. An AGVS leads to a more reliable process and therefore makes the connected processes more stable (Eriksson, 2017).

Besides these three groups of factors Knutsson (2017) mentions the importance of an organisation that is ready for the change that an automation implicates. He says that it is important that the management team is involved and engaged in the project. The whole organisation has to be prepared for the new technology and the staff educated to have an as successful implementation as possible.

4.3 Reference companies

4.3.1 Haldex

4.3.1.1 Company description

Haldex is a Sweden-based company with its headquarters in Landskrona. It operates in 18 countries and has 2100 employees (Haldex AB, 2016a). Haldex develops, produces and sells brake and air suspension products for heavy vehicles (Haldex AB, 2016b).

The interview with Haldex was held with Anne Andersson, Shift Leader at Haldex in Landskrona. The interview took place at Haldex's office in Landskrona, where a visit to the production area in which the AGVs operate in also took place.

4.3.1.2 The company's use of AGVs

In the end of 2013 Haldex implemented two forklift AGVs with space for a human in their production in Landskrona. The AGVs are from Toyota Material Handling (Andersson, 2017).

Process description

Haldex's AGVs move pallets between production lines and to the shipping area. Only pallets are moved. These are collected and delivered to and from floor spaces, racks and conveyor belts. There are sensors on the conveyor belts that let the AGV know if there is something to pick up. A button at the pickup place can also be pushed to request a pickup (Andersson, 2017).

At Haldex the AGVs work in the same environment as humans and manual forklifts.

Reason for implementation

Andersson (2017) was not part of the project when the implementation of the AGVS started in 2012 and does therefore not know what the exact reason for the implementation was. She does however mention that the reason for implementation was probably because someone saw a possibility to improve productivity and cut costs.

Description of the company's AGVS

Haldex uses Toyota Material Handling's guidance control system for their AGVS, Andersson (2017) does however not know if this is connected to an ERP or WMS system. The guidance control system shows where the AGVs move and where they are at a specific time.

The AGVs navigate with laser navigation. Andersson (2017) is not sure why this navigation method was chosen, but it has according to her worked well. The only problem that occurs is when you move a reflector, even if only slightly, and when pallet racks are moved. Andersson (2017) does however point out that they have gotten good support from Toyota Production System in these cases.

The AGVs do not work with obstacle avoidance. Instead they simply stop if something is in the way (Andersson, 2017).

Haldex's AGVs are equipped with the standard safety equipment, they did not choose to add any extra safety technology. In order to make the production environment safer they educated the employees, that operated in the same area as the AGVs, how to handle the vehicles (Andersson, 2017).

The batteries used for the AGVs are lead-acid ones. Haldex has two normal shifts as well as parts of the production open at night. The AGVs' batteries last for this whole time, meaning 24 hours (Andersson, 2017).

4.3.1.3 Results of implementation

Issues during implementation

Haldex had some major issues with the connection to the WLAN and the access points when implementing the AGVS. Andersson (2017) appreciates that it took around 1.5-2 years before the WLAN connection for the AGVs worked properly. The WLAN could at this time shut down which resulted in the AGVs not working. It turned out that part of the problem was because of a programming error in the AGVs. Today the WLAN problems are solved and everything works very well.

In the beginning Haldex had problems with the employees working together with the AGVs. Some manual forklifts accidentally hit the AGVs and some people were afraid of them. After some time the personnel learnt how to work with the AGVs and understood that an AGV always does the same thing. "If you learn how it acts and where it drives it will never surprise you with its behaviour as a person might." (Andersson, 2017).

Another problem area in the beginning was that people were used to be able to put pallets in the aisles when needed. They were also told to put out traffic cones in the lanes when working in an area so that an AGV would stop further away from the person working. These pallets and traffic cones made the AGVs stop often and affected productivity. By educating personnel and introducing one-way traffic for the AGVs people learnt how to cooperate with the AGVs and got extra working space in the lanes. This solved the problem and productivity has since then increased (Andersson, 2017).

According to Andersson (2017) the employees in the production area handled the implementation of the AGVS well. In the beginning someone could say a snide comment about people having to leave the company because of the AGVs. Now they are just happy that they do not have to handle the boring tasks the AGVs do themselves (Andersson, 2017).

A problem that Haldex still has is their floors. If a hole is created in the floor and an AGV hits this spot it can lose its path. If this happens the AGV will stop and needs be to manually started again. Haldex continuously works with fixing holes like this in their production (Andersson, 2017).

Achieved results

According to Andersson (2017) Haldex is satisfied with their AGVS. Before they learnt how to work with the AGVs there were some problems but these are now solved. She says that the main contribution from the AGVS has been increased safety. According to her the production environment feels safer as an AGV would for example never drop a pallet.

Haldex will soon implement an additional AGV. They will in this case not change any features such as navigation, energy supply or which supplier they will use (Andersson, 2017).

Andersson's (2017) key learning point, and recommendation from Haldex's AGVS implementation is to have the IT-department on-board when doing a project like this. IT-issues can cause a lot of problems.

4.3.2 SKF

4.3.2.1 Company description

SKF is the largest manufacturer of bearings in the world with its headquarters in Gothenburg; where it was founded in 1907. It operates in 32 countries and employs 47 000 people (Skf.com, 2017a).

The interview was held with Peter Schmid, Demand Change Project Manager in Steyr, Austria. The interview was conducted over the phone and therefore the process, where the AGVs operate, could not be observed. DS-Automotion, that supplied the AGVS, has however filmed the whole operation[14] and the AGVs could therefore be observed.

4.3.2.2 The company's use of AGVs

SKF implemented two forklift AGVs with space for a human at Steyr, Austria, in 2014. The AGVS was supplied by DS-Automotion (Schmid, 2017).

Process description

The AGVs at SKF work with three different material flows. The first flow is to supply the production area with material from the component warehouse. The second flow is to return material that was not used from the production area back to the component warehouse. The third flow is delivering finished goods from the production area to a centralised picking area. In total these three flows sum up to 300 transports a day. The load carrier at SKF in Steyr is completely standardised. The material is loaded on half-pallets with either one or two collars (Schmid, 2017).

The AGVs operate in an environment where both pedestrians and manual driven forklifts operate (Schmid, 2017).

Reason for implementation

SKF experiences a lot of volatility in the demand and has had problems handling the peaks. The peaks led to an increased level of stress for the employees that were responsible for the replenishment of goods from SKF's component warehouse. This resulted in increased risks regarding safety and quality since the employees drove faster than allowed and often delivered the wrong material. To avoid these stressful tasks AGVs were implemented. Reducing costs was not one of the major incentives for implementing an AGVS, instead it was a safer working environment and increased quality of their processes (Schmid, 2017).

Apart from the above mentioned reason for implementation another factor was SKF's strategy to automate its production as much as possible (Schmid, 2017; SKF, 2017b).

Description of the company's AGVS

SKF uses DS-Automotion's guidance control system that communicates with SKF's internal WMS system. When the AGVS was implemented SKF added additional access points where the vehicles operate in order to secure a strong connection to the WLAN. The AGVs run on a separate frequency and they have not had any issues with the connection (Schmid, 2017).

SKF has chosen to use artificial laser navigation as the navigation method for their AGVs. In the pre-phase of the project five different suppliers were invited to bid on the proposal and all of them suggested artificial laser navigation. The suppliers argued that artificial laser navigation is a thoroughly tested method that has been used for 10-15 years. Schmid (2017) argues that artificial

[14] https://www.youtube.com/watch?v=DYSarQqrEww

laser navigation provides the flexibility that is needed since they can easily move pick up and drop off locations without any additional infrastructure installations.

SKF's AGVs do not work with obstacle avoidance. Instead they stop if something is in the way and utter a sound (Schmid, 2017).

The AGVs are equipped with the regular safety equipment that is legislated. In addition to this two additional safety sensors have been added. These are placed at the side of the vehicle to identify obstacles that the floor sensor does not see, for example ladders, see figure 4.5. The sensors were added on request by SKF's safety department. Schmid (2017) does not know if they have been necessary or not.

Figure 4.5 - SKF's AGV with two additional sensors at the side (Schmid, 2017)

The AGVs use lead gel batteries that, according to Schmid (2017), last for 24 hours before they have to be recharged. They manually swap their batteries at the beginning of the first shift of the day.

4.3.2.3 Results of implementation

Issues during implementation

Schmid (2017) admits that the learning curve for this project was quite long, six to seven months. It took time for the employees to get used to the vehicles and the additional traffic that was added. This led to unnecessary stops since people or other obstacles blocked the AGVs' paths. This was solved by deciding that the AGV always has priority in traffic situations.

One issue that Schmid (2017) points out is that the safety sensor at the bottom of the vehicle is not integrated into the vehicle and is therefore exposed. They have had accidents when manually driven forklifts have damaged the sensors, which has led to unnecessary costs.

During the beginning of the implementation SKF had issues with sunlight that disturbed the navigation sensors on the AGVs. At their facility in Steyr there are a lot of big windows and the supplier said from the beginning that this could cause issues for the AGVS. This was easily fixed by placing covering film on the windows. The floor in the facility was also an issue and had to be renewed at certain locations (Schmid, 2017).

Schmid (2017) points out that there was one issue that was not taken into consideration in the beginning of the project. In the process where the AGVs operate they collect pallets from the component warehouse; pallets that were placed there by manual forklifts. The AGV requires that the pallet is placed within +-10 mm from the predetermined location or it will not be able to collect it. This is an issue since humans are not as precise as robots. This was solved by installing fixtures at the pallet locations but has imposed an additional cost to the system.

Achieved results

The implementation of the AGVS has been successful and has solved the issue that SKF had. With this automation SKF now has a greater process stability and control, and can handle the demand peaks in a safe and controlled manner (Schmid, 2017). Schmid (2017) believes that even if it was a long learning curve, the employees welcomed the change since the AGVs were implemented to solve an issue and not to cut costs. The issue, that was the reason for the implementation, caused an increased level of stress and the AGVS has therefore led to a better working environment.

Since the AGVs require an obstacle free environment in order to run smoothly SKF has had to introduce new routines to keep the paths clear. This has led to increased orderliness in their production area and an overall cleaner facility (Schmid, 2017).

4.3.3 Systemair

4.3.3.1 Company description

Systemair is a Swedish company with headquarters in Skinnskatteberg. It has subsidiaries in 49 countries and a total of 4800 employees. The company was founded in 1974 and manufactures ventilation products (Systemair.com, 2017).

The interview with Systemair was held with Anders Westling, Maintenance Supervisor at Systemair in Skinnskatteberg. He was responsible for Systemair's AGVS implementation project in 2014. A visit to the production to see the AGVs was done at the same occasion.

4.3.3.2 The company's use of AGVs

Systemair implemented their first AGVS in 1998. The AGVs were in 2014 changed to newer ones and the guidance control system was upgraded. They now have eight forklift AGVs without space for a human. All AGVs at Systemair, during both implementations, have been supplied by AGVE (Westling, 2017).

Process description

Systemair's AGVs move pallets between production lines and to the shipping area. The system works on two different levels in the facility. When a pallet needs to go from one floor to another the AGV leaves it in an elevator that takes it to the other floor. The pallet is then picked up by another AGV. The elevator is connected to the guidance control system (Westling, 2017).

At Systemair the AGVs work in the same environment as humans and manual forklifts. According to Westling (2017) this works well.

Reason for implementation

Westling did not work at Systemair when the first AGVS was implemented in 1998 (Westling, 2017). Because of this he does not know the details connected to the decision to implement an AGVS at that time. He does however mention that the company was growing and that they needed more resources. They could either implement AGVs or hire more personnel, and they chose to try AGVs. In

2014 they brought in new AGVs since the repair costs of the old ones had become too high and spare parts were hard to find. It was calculated that it would be cheaper to buy new ones.

Description of the company's AGVS

Systemair uses AGVE's guidance control system for their AGVS. This is connected to Systemair's ERP system Movex. The guidance control system was together with the AGVs changed in 2014.

The AGVs navigate by active inductive guidance. This was the best alternative when implementing the first AGVS in 1998 and since the infrastructure of wires in the floor existed during the second implementation in 2014 they continued with this method (Westling, 2017). Westling (2017) thinks that the navigation works well but that it is not that flexible. He says that if they had a more flexible navigation method they might have changed the paths of the AGVs without the amount of consideration that goes into a change today. He does however add that maybe that is a good thing, now they really think through the changes made which makes many of them more successful.

The AGVs do not work with obstacle avoidance. Instead they stop if something is in the way (Westling, 2017).

Systemair's AGVs are equipped with mechanical safety bumpers in addition to the classical safety scanners that all AGVs have. This is standard for AGVs supplied by AGVE. Systemair did not choose to add any additional safety equipment on top of this (Westling, 2017).

The batteries used for the AGVs are lead-acid ones and Systemair do a manual battery swap of these when needed (Westling, 2017).

4.3.3.3 Results of implementation

Issues during implementation

Systemair had some problems during the implementation of the AGVS in 2014 linked to the WLAN. One AGV sometimes lost its WLAN connection at a certain location and shut down. The AGV then had to be manually removed from the guide path. Since it was not possible to disconnect the AGV from the guidance control system the other AGVs thought that it stood in the position where it had stopped. Because of this the AGVs stopped when they reached this spot, thinking that something was in the way. This could be solved by connecting the AGV that had shut down to the WLAN through a cable and was later solved permanently by AGVE. Except for this issue connected to one AGV Systemair has not had any other problems with the access points or the WLAN connection (Westling, 2017).

Systemair has had some troubles with sunlight hitting the prongs and the safety sensors, which lead to unnecessary stops. This was easily solved by applying a protective film on the windows where the sunlight came in (Westling, 2017).

In the beginning the AGVs sometimes accidentally drove too far when picking up a pallet, making the prongs hit the wall behind the rack. This happened because of a programming error and has now been solved. It did not cause any major damages (Westling, 2017).

Systemair has also had some problems with manual forklifts accidentally driving into the AGVs because of recklessness or because the drivers have been stressed. To help this problem Systemair has informed the forklift drivers about the costs of the different parts of the AGVs, and how they differ from regular forklifts, so that they will be more careful (Westling, 2017). In general Westling (2017) thinks that the cooperation between humans and AGVs has worked well.

To have good floors has according to Westling (2017) been a critical factor for the AGVS to work properly.

Achieved results

Westling (2017) states that Systemair is satisfied with their AGVS. He says that the main contribution from the AGVS has been that people do not have to execute unnecessary and simple transportation jobs.

Systemair is looking into an implementation of another AGVS at another production site in Skinnskatteberg. They will in this implementation probably use laser navigation as there is no existing AGV infrastructure at this site. Systemair will also look into AGVs that can lift six meters high and possibly have longer forks. They will have the same energy supply system and continue using AGVE as a supplier (Westling, 2017).

5 ANALYSIS

This chapter contains an analysis done area by area as in Chapter 3 and parts of Chapter 4. Information collected from theory and interviews is combined and discussed to get an as broad perspective of the AGVS technology as possible.

5.1 AGV TYPES

5.1.1 Categorising AGVs

After studying AGVs it becomes increasingly clear that there is no established nomenclature for different AGV types. There is also no standard categorisation of the different AGVs.

Ullrich (2015) has in his book *Automated Guided Vehicle Systems* named the different types of AGVs but has not motivated his chosen names. The suppliers have named their AGVs differently as well. The biggest difference occurs in the names of forklift AGVs with or without space for a human. Names for AGVs with space for a human vary from Ullrich's (2015) Forklift AGVs as automated Serial Equipment to Toyota Material Handling's name AGFs (Automated Guided Forklifts) to Egemin's Hybrid AGVs. Forklift AGVs without space for a human are by Ullrich (2015) called Specially Designed Forklift AGVs, by Toyota Material Handling AGVs (Automated Guided Vehicles) and by Egemin Standard AGVs.

What the different categories are called is not important when using AGVs but a common nomenclature at Scania will simplify conversations about the AGV types, especially in the planning and implementation phase. The authors of this report therefore recommend that the names stated in table 5.1 are used. Here a forklift AGV with space for a human is called a Hybrid Forklift AGV and without space for a human a Standard Forklift AGV.

The names chosen by Ullrich (2015) are descriptive but considered too long to use in daily conversation. Toyota Material Handling's name, AGF is descriptive and easy to use but its counterpart AGV for forklift AGVs without space for a human is considered confusing. It shares the name of the whole group of robots and can therefore be misinterpreted. Egemin's names, Hybrid AGV and Standard AGV, are considered clear and descriptive. AGVE also uses the name Hybrid AGV for their forklift with space for a human. Hybrid AGV is an intuitive name if knowing that forklift AGVs are the topic. By the suppliers interviewed it is also the most commonly used name. To make this more coherent the name forklift is added in the names of the types and the result is Hybrid Forklift AGVs and Standard Forklift AGVs.

As mentioned earlier in this report Ullrich (2015) has the opinion that the best way to categorize AGVs is by looking at the loads they transport. This advice will in this report be followed even if some of Ullrich's (2015) names are changed.

Toyota Material Handling has chosen to divide their underride AGVs in two categories, AGCs (Automated Guided Carts) and AMRs (Autonomous Mobile Robotics). Even if it is considered good to know the difference between the two types of vehicles they will not be included in the official categorisation. The reason for this is that, even if they are different and are suitable in different environments, still carry the same loads and transport their loads in the same way. The recommended categorisation is illustrated in table 5.1.

Table 5.1 – The recommended categorisation of AGVs

Load	**Type of AGV**	
Pallet	Hybrid Forklift AGV	
	Standard Forklift AGV	
	Piggyback AGV	
Trailer	Hybrid Towing AGV	
	Standard Towing AGV	
Cart	Underride AGV	
Special loads	Special Design AGV	
Assembly objects	Assembly AGV	

5.1.2 Hybrid or Standard Forklift AGVs

When choosing whether to implement Hybrid or Standard Forklift AGVs there are as mentioned in both subchapter 3.1.1 and 4.2.2.1 advantages and disadvantages with each. For abnormal situations like heavy goods, extreme temperatures or for special operations it seems to be accepted that Standard Forklift AGVs are most suitable as it is easier to customize them. For standard operations there does however not seem to exist an obvious answer. The advantages with each type in standard operations, stated by literature and suppliers, are presented in figure 5.1. There is no right answer when it comes to which type of Forklift AGV that is the best, all arguments have to be read and weighed depending on the situation. Will people break the AGVs if driving them manually? Can AGVE really offer Standard Forklift AGVs to the same price as Hybrid Forklift AGVs? Is the psychological factor that comes with a Hybrid Forklift AGV important? The answers to all these questions all depend on how the AGVs will be used and to a certain extent on company culture. There is also the aspect that some of the arguments can be applied to the other type as well. One of

Ullrich's (2015) arguments for Standard Forklift AGVs is for example that they can be used with automatic battery swapping. Based on the interviews with the suppliers made for this master thesis there is nothing that indicates that this would not be possible for a Hybrid Forklift AGV.

Hybrid Forklift AGVs	Standard Forklift AGVs
• Can be made out of serially produced forklifts on a line which leads to a cost advantage (Ullrich, 2015; Van Bergen, 2017; Eriksson, 2017; Gartner, 2017). • Have proven service and replacement part availability as they often come from established forklift companies (Ullrich, 2017). • Have an advantage when service or maintenance is to be executed as an employee can step into the AGV and drive it to the maintenance area (Eriksson, 2017). • Give a psychological feeling of safety to the employees as a manual forklift is something they recognize (Eriksson, 2017; Van Bergen, 2017). • Mean less change in the processes as the AGVs can still be used manually for some activities (Van Bergen, 2017).	• Can be built on a line with serially produced forklifts which leads to a cost advantage (Dannemark, 2017). • Are designed for permanent use and extended service life (Ullrich, 2015). • Function well with an automatic-compatible energy concept with the possibility of automatic battery change or charging (Ullrich, 2015). • Are not possible to drive in a manual mode which makes it harder to break the expensive equipment on them (Dannemark, 2017).

Figure 5.1 - A summary of the presented advantages with Hybrid Forklift AGVs and Standard Forklift AGVs in this report.

5.1.3 Other AGV types

Looking at the AGV types presented in table 5.1, forklift AGVs are probably the type that has the largest area of use at Scania as the company today uses many forklifts. Outdoor AGVs fall under the category Special Design AGVs and have a possible field of application at Scania on the path from the logistic centres to the production units. Most suppliers do not make outdoor AGVs but AGVE has found a solution that they think works well. It is up to Scania to evaluate if AGVE's solution would work for their operations. Another AGV that could be applicable is the Underride AGV. This type could be used to transport carts with kitting material from the platforms to the production line.

Towing AGVs could also be used at Scania to replace the logistic trains. In some operations it would be possible to change the manually driven train to an AGV and keep the process the same. It is however not certain that a vehicle should always be changed to its equivalent AGV type. Logistic trains are according to de Vries (2017) used because of two reasons; to increase the level of safety by decreasing the amount of forklifts used and to gain control of the process and synchronise it with the production's takt time. The argument for logistic trains connected to lowering the amount of forklifts at the production unit is a strong one at Scania. Forklifts are connected to danger and are therefore in many cases tried to be eliminated. A problem here is that the employees might not see that the forks are, in the absolute majority of the cases, not the dangerous part of a forklift; it is the human driving them. There could therefore be strong resistance against forklift AGVs even if they are not dangerous. If overcoming this fear of forklift AGVs the possibility could be opened to change a logistic train to several forklifts or other types of AGVs even if it initially might feel like going backwards. The argument connected to gaining control of the process and synchronising it with the takt time point towards changing the current logistic trains to Towing AGVs. If a solution could be found with Forklift or Underride AGVs that gives the same effect this could however also be a valid alternative as some problems still exist with Towing AGVs.

During the research for this report there has been no valid and fully functional solution found for how to execute the load transfer for a Towing AGV automatically. This means that the human that was driving the logistic train before is still needed for the load and unloading part of the operation. One person might be able to handle the load transfer for two Towing AGVs but it would not be possible to remove one person per train. This makes it harder to defend the investment that an implementation of a Towing AGV requires. Another aspect of the Towing AGV is that it can have some safety issues. These will be more thoroughly described in the safety part of the analysis (subchapter 5.5). In short a Towing AGV has blind spots as there are no safety sensors on the wagons. This means that if someone is standing between the wagons the AGV will not notice it. In order to solve this the AGV either has to accelerate very slowly so that a person standing between the wagons can move away or safety sensors have to be added to each wagon. This will either lead to less productivity because of the lowered speed or additional costs because of the additional sensors. An alternative is instead to use one AGV for each wagon. If the wagons contain pallets forklift AGVs could be implemented. If they contain kitting carts, which they do in most cases, an Underride AGV could be used for each wagon. These AGVs will be able to do the load transfer themselves, not have safety problems and probably be able to move faster than a Towing AGV. The increased cost of having several AGVs instead of one Towing AGV has to be weighed against the advantages of course. Evidence of a used and fully functional solution like this with underride AGVs has not been found anywhere but will most likely be more common when the technology is more developed. This solution also has to be weighed against de Vries' (2017) argument that logistic trains lead to increased control and the ability to synchronise the process with the takt time. This could however still be done as a group of AGVs could be programmed to move in a similar way as a train, but with the load transfer problem solved.

5.2 The AGV guidance control system

The different suppliers' guidance control systems work similarly and only differ in the service functions that they offer. Some of them are more advanced and can act as warehouse management systems as well, in addition of the normal service functions. Which guidance control system to choose is therefore not the question that has to be asked when implementing an AGVS. The topic is instead whether a guidance control system is needed for the task the AGV is to perform and how to solve the issues regarding wireless communication.

A guidance control system is not a necessity if an AGV is operating alone and does not need to cooperate with other AGVs. These are rare situations and are mainly isolated material flows. Most positions at Scania are required to follow the takt time which requires communication with the internal logistic operational system through a guidance control system.

An issue that is vital when it comes to the guidance control system is the need for a strong and reliable WLAN connection. This is a requirement that many suppliers mentioned and an issue that, for example, Haldex had. Because of the environment in which the AGVs operate many factors will affect the WLAN connection. Factors that disturb the connection can be other frequencies, surrounding materials such as iron as well as welds; elements that Scania has in its production today. This means that Scania could have problems with their WLAN and that possible issues with the WLAN have to be taken into consideration early on in the project. SKF has a similar production area as Scania and they did not have any issues with the connection since they were aware of the importance of a well-functioning connection and because of this secured a strong connection early on in the project.

Because of the importance of a well-functioning WLAN for an efficient AGVS many suppliers want to have control over the WLAN. The supplier will therefore probably want to install their own WLAN in order to have full control of the system and any issues that might occur. This is not a necessity when implementing an AGVS but it is important to have a discussion with the supplier regarding these questions. A solution that Knutsson (2017) from Jernbro mentioned is to allow the AGVS to run on a separate frequency so that it will not be disturbed by factors that are not connected to the AGVS. This is something SKF has done with a good result.

In the interview conducted with Granqvist (2017) from Scania he mentioned something he learned from a project in Oskarshamn. The project implied that a device, that required a WLAN connection, was installed to the forklifts in the production area. The devices were programmed to hold their connection to a certain access point until it was out of range and only then move to the next one. This caused them to lose the connection even if the WLAN was strong in the entire facility. Instead the device should automatically connect to the access point with the strongest signal and therefore switch access points while traveling. In this case it was not an AGV that was installed but Granqvist (2017) said that an AGV could have the same issue. Programming issues are something that both Systemair and Haldex mentioned as well and therefore, as mentioned earlier, it is of importance to discuss these issues early on with the supplier.

If using different suppliers of AGVSs it is important to know that their guidance control systems cannot cooperate. If the AGVs from the different systems are to interfere with each other the overall efficiency will decrease. The AGVSs would then have to be separated geographically since they cannot communicate in an efficient way with the AGVs from the other system. They can be separated by setting up traffic lights or horizontal bars but the best thing is to separate AGVSs from different suppliers completely.

The issue connected to the guidance control system is mainly to secure a stable and reliable connection to the WLAN. Because of the setting in which the AGVs are operating there are many factors that will cause issues and with that affect the efficiency and reliability of the AGVS. To solve this issue it is important to involve the IT department early on in the project and to discuss the issue with the supplier. One of the reasons why Scania initiated this thesis project was to make sure that the implementation of AGVSs is done in an organised way. By implementing AGVSs from many different suppliers problems might arise in the future where the different guidance control systems impedes Scania from achieving the full efficiency of the technology.

5.3 Navigation methods

Based on the information gathered from theory and suppliers it is clear that there is a great number of navigation methods for AGVs. Some were developed and used in the 50's already, like passive and active inductive guidance as well as optical guidance, and some new methods have been developed, like laser navigation and magnet spot navigation. The early techniques are still used to some extent today. Most suppliers do not see them as relevant methods however as they do not provide, according to them, the flexibility required of an AGVS. The majority of the suppliers interviewed for this master thesis prefer a newer method, artificial laser navigation. Before implementing their AGVS SKF talked to many different suppliers and came to the same conclusion. Suppliers recommend artificial laser navigation for most applications and see the other methods as alternatives for special cases when artificial laser navigation is not suitable for some reason. This is a flexible method and has according to theory and the majority of the suppliers the highest precision and performance compared to other methods. It has been used for a long time and is therefore also well tested. There are however some situations where this method is not appropriate and another method should be chosen. If having an environment with a lot of dirt, as contamination in the air or dirt on the ground, it can be a problem as it disturbs the reflection of the reflectors. Another issue that SKF had problems with was sunlight as it can disturb the scanners. This was however easily solved with a protective film on the windows. Furthermore there are some types of AGVs that are not suitable for artificial laser navigation, for example Underride AGVs where the laser scanner cannot be placed in a good location without having the laser scanner disturbing the employees.

According to Gartner (2017) from DS-Automotion fixed-path navigation methods are mainly for assembly line AGVs. Assembly line AGVSs have different requirements than AGVSs for intralogistic processes as reliability is, for them, considerably more important than being flexible. The continued relevance for this type of AGV today explains why fixed-path navigation methods are still a researched topic. For intralogistic processes the fixed-path navigation's field of application is quite limited. It has the advantages of being cheaper and having different requirements on the environment but is at the same time inflexible and does for some methods not provide the same precision. With this method AGVs can be used in surroundings where laser navigation would not be an option. Dannemark (2017b) from AGVE mentions many situations where it is the most valid method, for example when an AGV needs to operate in high temperatures or other aggravating environments. It is also a good method for outdoor applications. Knutsson (2017) from Jernbro also adds that for some applications it is not cost efficient to have an as advanced system as artificial laser navigation because of lower requirements of precision, performance and flexibility.

Contour navigation is another navigation method on the market. This method provides higher flexibility than artificial laser navigation as it operates without reflectors. All suppliers talked to during the execution of this master thesis are either investigating or are already offering this method, which indicates that it is an upcoming technology. The fact that contour navigation does not need reflectors means that racks can be moved more freely than with artificial laser navigation. Haldex uses artificial laser navigation and Andersson (2017) mentioned that if they want to move a rack with a reflector on it the AGVS has to be updated. With contour navigation this is not necessary even if a certain percentage of the environment has to stay the same for the AGVS to work. Dannemark (2017b) means that this percentage is 30-40 per cent while Gartner (2017) says 50 per cent. This is a limitation in an industrial environment where the production area can change. Another disadvantage with contour navigation is that it lacks operating time in an industrial environment and has, compared to artificial laser navigation, not been as thoroughly proven to work. A lot of work to develop this technology is done and the percentual need for a constant environment will decrease which will make the technology more suitable for industrial environments.

During the interview with Gartner (2017) he mentioned that DS-Automotion can combine the navigation scanner for contour navigation with the safety scanner. This leads to a decreased cost for each AGV and will make this technology even more cost efficient. Of the interviewed suppliers DS-Automotion was the only one that mentioned this which might indicate that the technology is still in an early stage. An additional cost advantage is the decreased installation cost for contour navigation since reflectors are not required. How much this affects the total cost of the system is still uncertain since the suppliers had different opinions regarding this. Eriksson (2017a) from Toyota Material Handling says that the cost for artificial laser navigation and contour navigation is approximately the same, regardless the decrease of installation cost, while Dannemark (2017b) from AGVE means that it would decrease the total price.

Hybrid navigation, a combination of artificial laser navigation and contour navigation, is interesting since it benefits from the advantages of both methods. Both the increased flexibility from contour navigation and increased precision from artificial laser navigation are achieved. This method is not well tested in operation neither but will, just as contour navigation, be further developed.

Scania is, in this case, investigating the possible use of AGVs for intralogistic processes within its production. In this field of application, flexibility and reliability is of high importance. Artificial laser navigation is therefore considered the most suitable solution for most processes at Scania today. The fact that artificial laser navigation is a well-tested technology is in line with Scania's strategy connected to not implementing untested technologies like stated by Arnstedt (2017). As the technology has some flaws it is important to still be open for other methods. Hybrid navigation and contour navigation are interesting alternatives but the technologies are still immature with no large scale comparable systems in use today. This does not mean that they should be entirely discarded as possible solutions but it is important to take into consideration that they are new and untested methods.

5.4 Obstacle avoidance

Obstacle avoidance is a subject where academia and practise disagree. According to theory obstacle avoidance is an issue that has to be solved in order for the current AGVS technology to continue developing. The suppliers do not agree with this. All suppliers are of the belief that obstacle avoidance is a way of solving an issue that should not be a problem in the first place. If there are obstacles in the AGV's path, such as pallets or manual forklifts, the issue is not how to avoid them but rather why they are there. It is a sign of issues in the process. By implementing AGVs that stop for obstacles these issues are visualised instead of the current situation where manual forklifts avoid the issue by finding an alternative path. By visualising the issue it can be handled and by that lead to increased orderliness and stability within the process. This was the case for SKF. They experienced that the implementation of AGVs resulted in a cleaner production area with increased control of their processes.

Another argument against obstacle avoidance is that for employees to cooperate with the AGVs they have to be able to predict their movements. In many cases AGVs and manual forklifts will operate in the same area. If the AGV is allowed to alter its predetermined path it will be harder to cooperate with it which will decrease the level of safety in the facility and the efficiency of the process.

In areas where there are a lot of material handling procedures, such as aisles with a lot of pallet positions, the AGV would have to stop and wait for other AGVs or manual forklifts to finish their tasks. It is for these situations that it would be efficient to let the AGV pass the obstacle to not form a queue and a potential bottleneck. AGVE has a solution for these situations. Since the loading positions are known and programed into the AGV at the beginning, alternative routes can be set up. When an AGV has to load or unload something in a position the guidance control system can order the other AGVs to take an alternative route and by that avoid the obstacle in a safe and predetermined way. If it is a manual forklift, that is not connected to the guidance control system, that has to load or unload at a position a button can be attached next to the pallet position. This can be pressed in a loading situation and the guidance control system will be informed that the position in question is blocked. These solutions are possible when the positions that can be blocked are known in advance and where there are safe alternative routes.

Based on these arguments it is concluded that obstacle avoidance is an unnecessary function that leads to more issues for an AGVS than the problems it solves. Since AGVs are used in many different applications obstacle avoidance should however not be entirely discarded as it might be of interest in other fields.

5.5 Safety

Based on theory and interviews with suppliers and reference companies there do not seem to be any considerable areas of discussion or disagreements when it comes to safety. The EN 1525 is a widely known regulation in the business and is always followed as much as possible when implementing an AGVS. Some suppliers choose to not follow it completely but give what the authors of this report consider to be valid reasons for not doing so. They also compensate with other safety functions to secure that the required level of safety is met. It is however always important that Scania does their own risk assessment in the case of an implementation to understand all safety aspects.

In general all reference companies seem to have chosen the standard safety equipment offered by the supplier and are satisfied with this. SKF is the exception as they have added two extra safety sensors on the sides of their AGVs to be able to detect a ladder or an obstacle that is sticking out from a shelf for example. This was requested by SKF's safety department and Schmid (2017) does not know if they have been useful or not. While it of course does not hurt to have these, except for the fact that they cost 30 000-40 000 SEK a piece, the question is if they are necessary. Just like people are arguing that obstacle avoidance is not necessary because people should learn to not put a pallet in an aisle in the first place, one could argue that there should not be a ladder standing in the way in an industrial environment. This is of course to be taken into account in the overall risk assessment of the system.

One aspect that should be given some extra attention, from a safety perspective, is load transfer. Ullrich (2015) mentions that this is a task that can be dangerous and Dannemark (2017b) recounted the story of a person breaking his or her foot in an AGV load transfer operation. While doing a load transfer operation the AGV has to disengage some of the safety features in order to pick up the pallet, for example. This makes the procedure dangerous and strict rules have to be applied for the employees' safety. Ullrich (2015) recommends to solve this by restricting access to relevant loading areas. This is not possible in most cases as all loading and unloading areas of an AGV can most likely not be restricted to humans. Where this restriction is not possible Ullrich (2015) recommends floor markers, designated danger zones, and visual and acoustic warning signals. In general it can be concluded that personnel working close to the AGVs should be educated in how the safety equipment on an AGV works and in which operations not to interact with the AGV or the load it carries.

Another area of interest from a safety perspective is Towing AGVs. Knutsson (2017) points out that the wagons connected to a Towing AGV do not have any safety equipment and therefore do not react if someone is standing between the wagons. Paulsson (2017) at Scania worries about this too. This problem can be handled in three ways; safety sensors could be put on each wagon, the AGV could be programmed to accelerate slower so that a person standing between the wagons can move away, or the problem could be discarded as the risk of a person going in between the wagons could be seen as very low. Alternative one would probably become too expensive to be a valid alternative, depending on how many different wagons that are used. Whether to then go with alternative two or three should be based on the risk assessment done by Scania. One should however take into account that if choosing alternative two there is a risk that the efficiency of the AGV goes down significantly as discussed in subchapter 5.1.3.

Based on the research done for this master thesis there does not seem to be any doubt that an AGVS is a safe installation and significantly safer than forklifts. In subchapter 3.3.1 in this report a comparison is done with self-driving cars where it is presented that crashes are 31 per cent more likely to occur per driven mile for a human-driven car than for a self-driving one. While these statistics are not directly applicable to an AGV versus a forklift they do say something about how human interaction can affect the safety of a vehicle. It is, as Paulsson (2017) at Scania says, important not to forget the new risks that can arise while eliminating old ones. In the case of an AGVS however it seems like the new risks are much fewer than the old ones and easier to manage since the AGV acts consistently. If wanting to hedge for safety problems even more it is, like mentioned earlier in the report, possible to add extra safety features. These can be mechanical bumpers on the AGV itself or the adding of traffic lights or horizontal bars in intersections as well as light and sound so that people know when an AGV is approaching.

5.6 ENERGY SUPPLY AND ASPECTS

5.6.1 Batteries and charging

There are many battery types on the market but only a few are used for AGVs. Ullrich (2015) means that lead-acid, lead gel and nickel-cadmium batteries are used in AGVs. When compared to what suppliers are using today this is not entirely true. Nickel-cadmium is in most cases not offered, partly because of strict environmental legislation. Lead-acid and lead gel are common and widely used. Lead-acid is appreciated both in theory and by suppliers for its robustness and the many years of development behind it. The battery also has the advantage that it is heavy which is good in counterbalance forklifts. Ullrich (2015) talks about nickel metal-hydride batteries but these have not been found to be used in practice.

The last battery type mentioned by Ullrich (2015) is lithium-ion. He talks about this battery as something of the future and says that they are not used in applications like AGVs yet. This is not the case anymore as it during interviews with suppliers turned out that they all offer AGVs with lithium-ion batteries. A lot of energy has been put into developing lithium-ion batteries the last couple of years, mostly because of the use within the automotive industry. Their price has gone down a great deal and will keep decreasing. As they are still expensive it is hard to defend them by comparing the payback time to other alternatives, but as their lifetime is longer than other batteries payback time is not a valid financial metric.

Based on literature and interviews with suppliers it is clear that a battery is chosen based on how the AGV can be charged and the charging scheme is based on what the AGV's operations look like. Choosing the wrong charging scheme might require a larger AGV fleet which leads to unnecessary costs.

While methods such as inductive charging are mentioned as an alternative both in theory and by the supplier Jernbro the most commonly used charging method seems to be charging different types of batteries by contact energy transfer. The charging schemes most used are manual and automatic battery swapping, opportunity charging and automatic charging. It is important to match the charging scheme to the operations. Opportunity charging should for example only be used if there sometimes are small breaks in the AGV's operation where it would have time to charge. Automatic charging is good if you have a battery that lasts through the shifts of the day and can automatically go and charge itself at night when it is not used. Battery swapping works in many situations but to do this automatically there needs to be a large fleet of AGVs and several shifts for the high cost of the battery swapping station to be economically defendable. AGVE mentions a method where an AGV is able to change the battery of another AGV which would make automatic battery swapping possible without any larger investments. This has not been mentioned in theory or by other suppliers which is why it is not considered a conventional and established solution. It is however an interesting topic to investigate further if automatic battery swapping would become an alternative for Scania. Manual swapping works well when an automatic charging station is not a good choice but for this to work there needs to be personnel available to do the swap.

Based on the decided charging scheme a battery should be chosen. Since lead-acid batteries need to be charged in full cycles (i.e. not five minutes here and there) they are good for battery swapping and automatic charging. Lithium-ion batteries are good for opportunity charging as they can be charged small amounts at a time. Lead gel batteries have the same qualities as lead-acid but do not create gas when charged, require less maintenance and charge faster. Jernbro and DS-automotion use them for battery swapping and automatic charging. Toyota Material Handling use lead gel batteries as well as lithium-ion for opportunity charging but do not let the lead gel batteries charge as short periods as are possible with lithium-ion as they do not have the same qualities. Larminie and Lowry (2012) also mention that they are more robust than lead-acid batteries and are for this reason more often used in electric vehicles.

Whatever charging scheme chosen it is important that it works logistically in the process where the AGV will work. If a battery that emits gas while charging is used there needs to be a space where this is not dangerous. It also needs to be possible for the AGV to get to the charging station. If a large number of extra reflectors and more WLAN access points need to be installed so that the AGV can get to its charging location this might not be a good solution. The increased operation area also makes the implementation harder. To make it a standard procedure that someone drives the AGV manually to its charging station every night is also debatable as this adds the risks connected to manual handling of the AGV which might lead to damage of the expensive sensors on the AGV. All this needs to be taken into consideration in a risk and cost assessment.

5.6.2 Energy results

Finally the question of whether an AGV reduces energy consumption will be discussed. Suppliers state that it does since an AGV drives more efficiently than a forklift driven by a human that breaks and accelerates unnecessarily often. Van Bergen (2017) points out that it is hard to say how much the energy consumption actually goes down.

In lack of statistics on the subject a comparison was once again made with manual and self-driven cars. In chapter 3.3.2 figure 3.21 was presented taken from a study on the energy consumption of manual and self-driving cars made by Wadud, MacKenzie and Leiby (2016). Of the factors mentioned in figure 3.21 there are few that can be applied to AGVs. Higher speeds might occur for AGVs but a more logical consequence would instead be lowered or the same speed as with manual forklifts or trains to not jeopardize the level of safety. Another feature that might be applied to AGVs is the increased weight of features, such as safety equipment in this case. These are however considered lightweight and the removal of a human would rather make the AGV lighter.

Since all the factors that Wadud, MacKenzie and Leiby mention that would increase energy consumption most likely can be disregarded, the conclusion can be drawn that the implementation of an AGV should decrease the energy consumption compared to a manual forklift or logistic train. The factor that is most likely to be relevant is what Wadud, MacKenzie and Leiby call eco-driving. This includes the minimization of repeated braking-acceleration cycles since breaking represents wasted energy, a phenomenon that is highly applicable to the driving of forklifts.

5.7 Environmental aspects

There are several environmental aspects that need to be taken into consideration when implementing an AGVS. Some are minor factors that only affect certain types of technological aspects while some are major and affect the efficiency of the whole system. The major factors are the condition of the floor, interference with pedestrians and manual forklifts and the WLAN connection. The suppliers mentioned many different factors but these three were the factors that all suppliers mentioned. These are also the factors that are described in theory.

The importance of the WLAN connection was discussed in subchapter 5.2 and the reason why it is hard to have a reliable WLAN connection is because of the environment where the AGVs are operating. The connection is disturbed by competing radio frequencies, welds and material made of iron. This is something that both Granqvist (2017) said and what Wilamowski and Irwin (2011) mention in their book. These factors are present at Scania's production areas today and will therefore cause issues for the WLAN connection. This does not mean that the sites are not suited for an AGVS but rather proves the importance of being aware of what might disturb the connection and because of that affect the performance of the system in a certain location.

The condition of the floor where the AGV operates is of high importance. This was something that was mentioned by the suppliers, the reference companies and also in theory by Ullrich (2015). It affects an AGV in several ways. An AGV requires advanced and expensive equipment such as laser scanners for safety and navigation. An uneven floor will cause vibrations that can damage this equipment. Since the scanners are fragile the AGV induces a higher financial risk compared to regular forklifts. The condition of the floor also affects the precision of the AGV. This is of high importance when carrying out loading and unloading procedures, especially with high lifting, since it otherwise will make the AGV unsteady. If the condition of the floor is so bad that it has holes in it, as in Haldex's case, it can cause damage to the AGV, disruptions in the operation and safety concerns as the AGV might do unpredictable stops. It is also important that the floors are kept dry and clean from spillage since this can lead to hazards causing the safety system to malfunction. Except for the evenness of the floor the shear strength of the floor is required to be high. The AGV always follows the same path and can therefore create tracks in the floor if it is not hard enough.

All suppliers recommend that AGVs and employees are to be separated as much as possible to achieve an efficient and reliable system. This is however impossible for many of Scania's processes. The AGV will in most cases operate in an environment where pedestrians and manual forklifts are present. The issue with this is that pedestrians will decrease the efficiency and the reliability of the system since they will interfere with its operation. To solve this the employees have to be educated early on in how the AGV operates and how they should act around it. All three reference companies recommended this since they all had a long learning curve before the employees accepted the robots. In addition to how to act around them it is important to clarify for the employees how an AGV and a regular forklift differ in value. Damages to an AGV might be much more financially severe than to a regular forklift.

The AGV requires that pallets and objects that will be loaded are placed in a certain location with high precision. Since the AGV cannot see the pallet, like a human can, it has to know where it is placed with a margin of error of +-10 mm. If this is not done it will not be able to identify the pallet. This limits the possibility of having AGVs and humans cooperating in the same process as a human needs to be very precise when placing a pallet in a location where an AGV will pick it up. This was an issue that Schmid from SKF mentioned. To make sure that the pallets were placed in the right location they had to install fixtures. At Systemair pallets were stored on the floor and carefully placed within a painted area. This is an issue that is important to take into consideration, it is always preferable to have the AGV pick up objects from fixed locations such as fixtures or conveyors.

These three factors are important to be aware of and need to be taken into consideration when implementing an AGVS. It can lead to a better and cheaper implementation since issues that might occur later on are avoided. Except for these major factors there are some minor ones that affect the choice of navigation method. It is important to know about these factors since they will narrow down the different alternatives of navigation methods for certain processes.

Laser scanners, which are used both for safety and in many cases for navigation, are affected by sunlight and dirt; both on the ground and as contamination in the air. The sunlight interferes with the scanners and causes the AGV to malfunction. This can however easily be solved by putting covering film on the windows. Dirt is a more serious problem and cannot be solved. The dirt covers the reflectors and disturbs the emitted laser beams. In environments where there is a lot of dirt other navigation methods should be used. Methods where the AGV follows a physical guide path attached to the floor, such as passive inductive guidance or optical guidance, are not good alternatives. The only methods that work are active inductive guidance or magnetic spot guidance since these methods will not be covered by dirt.

Methods that follow a physical guide path attached to the floor are limited in areas where there are crossing material flows by other AGVs or manual forklifts. Since the methods follow a guided path on the floor, either a magnetic or coloured strip, the system will be sensitive to tearing of that physical line. Ullrich (2015) says that an AGV running along a physical path can travel shorter distances without the physical path by using dead reckoning. The authors of this report do however still not see it as a relevant solution since the efficiency and reliability is decreased.

For special conditions the climate might affect the choice of AGV. When the climate varies from normalcy the use of AGVS technology is limited. This makes AGVs for outdoor applications complicated. The climate can also cause bad working environments for employees. In these cases an AGVS can be a solution to the problem since an AGV can be built to withstand hard conditions such as high heat, bad smell or other factors that make the working conditions poor. Toyota Material Handling had a case in the Netherlands where they supplied AGVs to a cheese factory since the smell was so strong in certain parts of the factory that no one wanted to work there. The climate can therefore also be a factor that makes an operation more suited for an AGV than a manual forklift.

The factors that have been mentioned in this subchapter are the ones that most suppliers thought to be the major ones. These corresponded to the ones mentioned in theory. The fact that the interviewed reference companies either have or have had issues with almost all of these factors confirms the authors believes that these are the most important factors to take into consideration when implementing an AGVS.

5.8 Operational aspects

The suppliers' opinions were very coherent regarding what factors that are decisive when analysing a process' suitability for an AGVS. The majority of the factors can be categorised as either process specific, product specific or financially specific. The specific factors should be used to evaluate if a process is suitable for an AGVS or not.

Process specific factors comprise the tasks that the process consists of and the environment in which the AGV operates. The environmental aspects have been discussed in the previous section and focus in this section will therefore be the tasks that the process consists of.

The first question that has to be answered is; can the process be clearly defined? The AGV operates after clearly defined rules. The tasks it will perform have to be defined in a way the AGV can easily interpret. If the process consists of complex tasks or many variations, for example caused by different materials, it will be harder to define the rules for which the AGV is to follow. This implies that the customer is required to have detailed information of the process and know the exact tasks that it involves. In a process there can be additional activities that are not defined in the process description; activities that once were a short term solution for a problem made by the operating personnel. These will cause issues since they might not be taken into consideration in the design of the system.

The second process specific question that has to be answered is; can the tasks that the process consists of be fully automated? To what degree the process will be automatized will determine the efficiency of the system and in the end the return on investment. A process could consist of tasks that have to be done manually such as opening a case or removing packaging. These are tasks that an AGV cannot perform and therefore require the presence of a human. This will lead to two consequences. With a human still present the AGVS will not reach its full financial potential. This might not be the case since a task instead could be done earlier or later in the process. The other consequence is that the AGV has to cooperate with a human which lowers the efficiency and might lead to complications. One of the purposes with automation is to remove the risk of human error. If the process is still dependent on a human the risk will remain.

The product specific factors are the aspects connected to the products that are handled in the process. The AGVS is affected by everything that defines how the product is handled. What type of load carrier, the quality of the load carrier, what the material looks like, how many product varieties there are, etcetera. The number of different products and load carrier varieties affect the complexity of the AGV. Many varieties imply that the AGV must be able to handle all of these in a secure and efficient way. This might limit the number of suitable suppliers since the level of customisation of the AGVS varies depending on the supplier. The question that can be asked regarding product specific factors is; how standardized are the load carriers? A higher level of standardisation makes the solution easier and leads to a more efficient system. An example for this is the reference company SKF. They only had one type of load carrier, half-pallets with two different heights, one and two collars.

The purposes of the process and product specific aspects are twofold. It is a way to decide if a process is suitable for an automation or not, but also a risk analysis to tell if the customer is ready for the implementation. For a supplier it is important that the information given by the customer is correct in order to take all valid aspects into consideration when designing the AGVS. The AGVS is programmed for a specific task with specific criteria and if those are not correct the system will not work properly. The success of the implementation is therefore partly dependent on the information that the system is based upon. This inflicts a risk on the supplier since it is measured on the final result. Even more so when it is the customer’s first implementation of an AGVS since it can determine the customer’s view of the technology. For the customer the risk is similar. Since it is a new technology for many the success of the first pilot project might be decisive if the company will implement it in larger scale or not. To conclude, the risk for the customer when implementing an AGVS decreases the more knowledge and control it has of its processes.

The financially specific factors indicate if a process is suited for an AGVS from an investment point of view. The purpose of implementing an AGVS might not be to cut costs but to increase the level of safety or to increase the control of a process. For those situations these factors will not have the same importance.

The question that has to be asked in this area is; how will an AGVS cut costs in this process? There are many ways in which an AGVS can reduce costs. The most prominent one is as a rationalisation investment and in that way cut costs by relocating employees. The factors that are decisive in these cases are the volume of the material flow where a higher volume indicates that it is a time-consuming task and the number of employees that can be relocated. The volume of the material flow is the leading indicator that a process is time-consuming. It is not enough to make a good business case however. As discussed earlier it is important that the automatization leads to the relocation of employees, otherwise the AGVS will only lead to an increased costs. It is therefore important to measure the savings by the number of employees relocated and not by the number of hours that have been freed up.

The implementation of an AGVS can potentially lead to more cost savings than from rationalisation. The AGVS both increases the quality of a transportation process and the process stability; both factors that can cut costs. A human driving a forklift can cause costs in the form of damaged infrastructure, equipment, goods and also damage to personnel. These costs are caused by human error and will be removed if the manual forklift is replaced with an AGV. An example of this was mentioned in subchapter 4.2.2.8 where Dannemark (2017b) mentioned a former customer that produced televisions and by implementing an AGVS was able to decrease the cost of damaged goods.

Another factor is the increased process stability. An AGV leads to an even flow of material. This increases stability for connected processes as well. The increased stability can enable a reduction of buffer storages and enable further automatization since the level of uncertainty is decreased.

These factors within the three categories of operational aspects are a simplified way of deciding if a process is suitable for an AGVS or not. All factors should not be seen as compulsory for a successful AGVS implementation, but instead examined to ensure that all categories are taken into consideration. A process can for example be suited for an AGVS if the tasks can be automatized in an efficient way, even if the material volume is low.

Knutsson (2017) from Jernbro also mentioned the importance of having an organisation that is ready for this kind of change. Change management is an important topic for big organisational changes as an implementation of AGVSs. This is not considered to lay within the scope for this master thesis and will therefore not be further discussed.

5.9 THE FUTURE

The future of AGVSs is hard to predict as the technological development moves forward in a fast pace. What Ullrich (2015) predicted to be the future in 2015 is in many cases already here. Lithium-ion batteries were for example not used in AGVs when he wrote *Automated Guided Vehicle Systems* and are today recommended by many different suppliers. These will, based on the research made for this report, be further developed and decrease even more in price to soon not just be a premium alternative.

Ullrich (2015) also mentions 3D obstacle recognition, speech guidance and swarm intelligence as future possibilities. These have been developed to different extents and could be interesting AGV aspects in in the future.

Another innovation that is under development is contour navigation. If this is developed into a reliable technology in industrial environments it will probably take a bigger market share than it has today and become a valid and trustworthy navigation alternative. This could decrease installation costs for AGVs since less or no reflectors will be used.

6 GUIDELINE

In this chapter the final guideline is presented. It is based on the analysis and covers how and where AGVSs should be used in an industrial environment.

One of the objectives of this master thesis is to create a guideline for how and where the AGVS technology should be used. The guideline is divided into two parts, illustrated in figure 6.1. One part is *How*, where the different AGV types and technology areas are described. The purpose with this part is to give a concise explanation of the different areas of the AGVS technology and important factors that need to be taken into consideration.

The second part, *Where*, is the result from the environmental and operational aspects that have been discussed in the thesis. The section is divided into three different categories containing aspects that are important to take into consideration when evaluating if a process is suitable for an AGVS or not. The aspects are simplified and should be used to give a first indication to whether a process is suitable for an AGVS. This should then be followed by a deeper analysis.

The guideline is constructed so that it can be extracted from the thesis and by this become more accessible. In order to give the reader the necessary information regarding an AGVS the guideline is accompanied by a glossary that gives a short descriptions of the specific AGVS terminology. This glossary can be found in Appendix E.

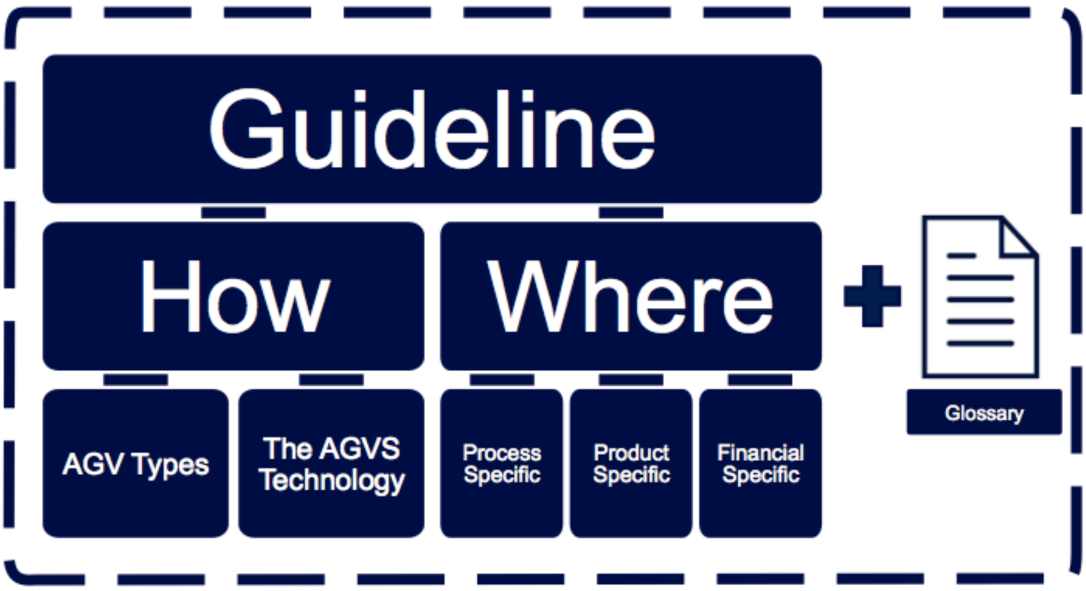

Figure 6.1 - An illustration of the structure of the guideline

6.1 HOW

6.1.1 AGV types

In table 6.1 a compilation of the different AGV types and their aspects can be found. There can be fields of application at Scania for many of these AGV types but it is recommended that Scania starts with an AGVS with forklift AGVs. These can be Hybrid or Standard Forklift AGVs. Both types have advantages and disadvantages to consider but are according to the authors of this report equal for standard operations if sold at the same price. When a pilot has been done with Forklift AGVs other AGV types could be looked into such as Underride AGVs, Towing AGVs and Outdoor AGVs.

Table 6.1 - A compilation of the different AGV types and their aspects

Load	Type of AGV		Aspects of the AGV
Pallet	Hybrid Forklift AGV		- Possible to drive manually - Can be used with all navigation methods even if laser is most frequently used
	Standard Forklift AGV		- Not possible to drive manually - Can be used with all navigation methods even if laser is most frequently used - Suitable for a high level of customisation
	Piggyback AGV		- Can carry pallets, boxes or containers - Requires a certain height which has to be maintained throughout the loading and unloading areas of the AGV - Lateral unloading which saves space and time - Suitable for customisation
Trailer	Hybrid Towing AGV		- Possible to drive manually - Can be used with all navigation methods even if laser is most frequently used
	Standard Towing AGV		- Not possible to drive manually - Can be used with all navigation methods even if laser is most frequently used
Cart	Underride AGV		- Requires little space as the load itself in most cases determine the space required - Hight manoeuverability - Cannot handle high weight loads - Cannot use artifical laser navigation because of its low height. Contour or fixed path navigation are the most frequently used metods.
Special loads	Special Design AGV		- AGVs for special conditions and operations - Can be an outdoor AGV or a heavy weight AGV for example
Assembly objects	Assembly AGV		- Fixed path navigation is most frequently used - Works in a slow pace

6.1.2 The AGVS technology

6.1.2.1 The AGV guidance control system

Most suppliers' guidance control systems work similarly and only differ in the service functions that they offer and the user interface. Some of them can provide more advanced solutions that can act as warehouse management systems. A supplier is therefore not chosen depending on the guidance control system they offer, if additional features are not of special value.

Important issues that have to be taken into consideration when implementing an AGVS are the WLAN and the use of different guidance control systems. An AGVS is dependent on a steady connection to the WLAN to enable reliable operations. This is an issue that is especially important in an industrial environment since there are many environmental aspects that affect the connection. These can be welds, iron and other competing radio systems that create electrical noise. Because of the importance of a reliable WLAN connection it is important to include the IT department in an AGVS implementation project.

Guidance control systems from different suppliers cannot communicate with each other in an efficient way. AGVS from different suppliers should therefore be separated within the same facility.

6.1.2.2 Navigation methods

In table 6.2 the different navigation methods that were researched for this master thesis are presented. There are many different techniques that can be used but the method most commonly used is artificial laser navigation. It is flexible and offers the highest precision. For some applications artificial laser navigation is not suitable. It is therefore important to know about the other methods and their strengths and weaknesses as there will not be one solution that fits all applications.

Table 6.2 - The different navigation methods

Fixed or open path	Method	Advantages (+) and disadvantages (+)
Fixed path	Active inductive guidance	+ Robust - Inflexible - Sensitive to metal in the floor
	Passive inductive guidance	+ Cheap + Easy to install - Sensitive to dirt - Sensitive to metal in the floor
	Optical guidance	+ Cheap + Easy to install - Sensitive to tearing from traffic - Sensitive to sunlight - Sensitive to dirt
Open path	Anchoring points	+ Cheap + Easy to install
	Artificial laser navigation	+ Flexible + High precision - Expensive - Dependent on reflectors - Sensitive to sunlight - Sensitive to dirt
	Contour navigation	+ Very flexible - Expensive - Untested in industrial environments - Requires a constant environment to a certain degree - Sensitive to sunlight
	GPS navigation	+ Possible to use outside - Cannot be used inside - Low precision

6.1.2.3 Obstacle avoidance

Based on the current technology, obstacle avoidance is not a required feature for an AGVS within an industrial environment. It can however be relevant for other purposes.

6.1.2.4 Safety

While safety is an important topic there are no considerable issues to take into consideration. All interviewed suppliers are considered to supply safe solutions. Focus from Scania should be to make a solid risk assessment. This should among other things include how to handle a situation where someone steps in between the wagons connected to a Towing AGV.

The EN 1525 regulation should, together with other relevant regulations, be considered. Extra safety features can be added in addition to what the suppliers offer as the standard safety solution. This can be extra sensors that detect obstacles that are above ground, designated danger zones and warning signals for load transfer, horizontal bars and traffic lights in intersections, etcetera.

6.1.2.5 Energy supply

When choosing an energy supply system for an AGVS one first needs to decide what charging scheme that is the most suitable for the processes. This should be based on the factors stated in table 6.3 but also by looking at what charging scheme works logistically. The charging station needs to be in an area the AGV can access.

Table 6.3 - The AGV charging schemes

Charging scheme	Can be used if:	Appropriate for type of battery
Manual battery swap	- There is personnel available to do the swap	- Lead-acid battery - Lead gel battery
Automatic battery swap	- There is a large AGV fleet and many shifts (to make the installation of the swapping station profitable)	- Lead-acid battery - Lead gel battery
Automatic charging	- The batteries can be charged at night - A battery can be chosen that lasts through all shifts of the day (otherwise the required AGV fleet will increase)	- Lead-acid battery - Lead gel battery
Opportunity charging	- The AGVs have many short predictable stops so that natural idle time can be used for charging	- Lithium-ion battery - (Lead gel battery, with longer minimum charging times than possible for lithium-ion batteries)

When a charging scheme has been chosen one should look at the different features for the batteries stated to be appropriate for the chosen charging scheme in table 6.4. Based on this a suitable battery should be chosen.

Table 6.4 - The AGV batteries

Battery	Advantages (+) and disadvantages (-)
Lead-acid battery	+ Heavy - good for counterbalance forklift AGVs + The cheapest rechargeable battery per kilowatt-hours of charge + Reliable technology because of many years of development - Gas is created when charging - Has to be charged in full cycles
Lead gel battery	+ Does not create gas + Charges faster than lead-acid batteries + Little maintenance needed
Lithium-ion battery	+ Does not create gas + Charges faster than lead-acid and lead gel batteries + Little maintenance needed + Does not have to be charged in full cycles - Expensive (prices are however decreasing)

6.2 WHERE

6.2.1 Process specific factors

The process specific factors comprise the tasks that the process consists of and the environment in which the AGV operates.

- ***Can the process be clearly defined?***
    - *Are the tasks within the process complex?*
    - *Are there many variations in the material flow paths within the process?*
- ***Can all tasks within the process be automated?***
    - *If not, can they be done in an earlier or later stage?*
    - *Can the current employee/employees be relocated?*
- ***Are there crossing material flows with manual forklifts?***
- ***Will the AGV cooperate with humans?***
- ***Are the floors in a condition that is suitable for an AGVS?***

6.2.2 Product specific factors

The product specific factors are the aspects connected to the products that are handled in the process.

- ***Can the load be handled automatically?***
- ***How standardised are the load carriers?***

6.2.3 Financial specific factors

The financially specific factors indicate if a process is suited for an AGVS from an investment point of view.

- ***How will an AGVS cut costs in this process?***
    - *Will it lead to rationalisation, and if so will it be possible to relocate the employee?*
    - *Will the increased quality decrease costs?*
    - *Will the increased process stability decrease buffer levels?*
    - *Does it enable further rationalisations?*

7 CONCLUSION

This chapter contains the conclusion of the master thesis. First the research questions are answered followed by a discussion about the limitations of the research done. Future research topics within the area are then suggested and the chapter is finally finished with a discussion about the master thesis' contribution to theory.

7.1 ANSWERS TO THE RESEARCH QUESTION

7.1.1 RQ1 – What does the AGVS technology look like today and what innovations are to come?

There are a number of aspects connected to an AGVS. In this master thesis the ones considered to be most important have been covered. These are the different AGV types together with technological aspects such as guidance control, navigation, obstacle avoidance, safety, batteries and charging.

7.1.1.1 AGV types

The AGV types have in this master thesis been categorised into eight different categories. These are Hybrid Forklift AGVs, Standard Forklift AGVs, Piggyback AGVs, Hybrid Towing AGVs, Standard Towing AGVs, Underride AGVs, Special Design AGVs and Assembly AGVs. There is an undergoing discussion in the AGV business whether the Hybrid Forklift AGV or the Standard Forklift AGV is the better choice. Based on the research made for this master thesis both are considered valid alternatives with different advantages and disadvantages. It is therefore concluded that if the AGVs will be used under normal conditions (i.e. no extreme temperatures or environments) and they can be found at the same price the choice is a matter of prioritizations and can be based on figure 5.1 in subchapter 5.1.2. If the Standard Forklift AGV is more expensive, like some suppliers state, a Hybrid Forklift AGV should be chosen.

The different AGV types come with different advantages. The Forklift AGV is the most common AGV since a lot of manual forklifts are used in material handling processes today and this is a natural change.

7.1.1.2 The AGV guidance control system

The guidance control system is the governing unit that enables communication between the different AGVs, peripheral equipment and the internal logistic operations system. The main task of the guidance control system is to manage the transportation orders. It handles the transport orders and delegates them to the AGVs so that they are handled in a safe and efficient way. The way the guidance control system manages the transportation orders does not differ between the different suppliers which is why it is not one of the factors that is audited when choosing a supplier. The guidance control system can however have additional service functions as well as more advanced functions such as the possibility to act as a warehouse management system. Which services the guidance control system offers differs between different suppliers.

In order to communicate the AGVS requires a reliable WLAN connection, a matter that can be an issue in an industrial environment. It is therefore important to involve the IT-department in the implementation project early on to avoid complications in a later phase.

Guidance control systems from different suppliers are not able to communicate with each other in an efficient way and it is therefore important to separate different AGVSs within the same facility.

7.1.1.3 Navigation methods

When it comes to navigation there are many different alternatives. They have their strengths and weaknesses and are all suited for different situations. What the methods have in common is that they all use dead reckoning to a certain degree. Dead reckoning is a way to navigate by measuring the velocity and the direction of the AGV. By knowing its starting position the AGV can calculate where it is compared to its original position. Dead reckoning is not precise and factors such as deviating radiuses of the wheels and weight of the load affects the calculated position. Because of this dead reckoning has to be complemented by another navigation method. These other methods are divided into fixed path and open path navigation.

The fixed path alternatives, those that follow a physical guided path, are active and passive inductive guidance and optical guidance. They were first introduced in the 50's and are still used to some extent. The main application area is assembly AGVSs because of the robustness of the methods. Active inductive guidance is when the AGV follows a current-bearing conductor inserted in the floor. The system is robust since the guide path is protected underneath the floor. It also enables the AGV to operate in tough environments where the environmental aspects prohibit the use of other methods and make the environment unpleasant for humans to work in. The downsides are the inflexibility since the wire has to be installed manually and that the performance of the system is low since the speed of the AGV is rather limited. An AGV with passive inductive guidance follows a magnetic strip that is fixed to the floor and one with optical guidance follows a painted line on the floor. They work similarly as the guide path is fixed on the floor. Compared to active inductive guidance these methods are more flexible and easier to install. The disadvantage is that the methods are sensitive to external factors such as dirt or crossing traffic since this can damage the physical guide path.

The open navigation methods operate along a virtual guide path that is programmed into the AGV. The different methods that have been researched for this master thesis are anchoring point navigation, artificial laser navigation, contour navigation and GPS navigation. There are other methods as well such as vision navigation or sonar navigation but they are, according to the authors of this thesis, not used in practise. The most prominent anchoring point navigation method is magnet spot navigation, a method where magnets are placed in the floor forming a grid inside the facility. The AGV takes bearings by measuring the distance to these magnets and can by this calculate its position. Magnet spot navigation is cheap and more flexible than the fixed path alternatives. The disadvantage is that the method is highly dependent on a well-functioning dead reckoning unit. Another version of anchoring point navigation is to use RFID tags instead of magnets. This works similarly to magnet spot navigation.

Artificial laser navigation is applicable for most situations. A rotating laser is mounted on top of the AGV. It emits lasers that is reflected on retro-reflecting foil that is mounted on walls and pillars above the workers' heads. The beams reflect back to the AGV and are then scanned. The coordinates of the landmarks are added to the map of the operating area when the system is set up. When the reflectors reflect the laser the AGV is able to triangulate its absolute position based on the knowledge of the coordinates of each reflector. Artificial laser navigation has high precision and it is not as dependent on the conditions of the floor as other methods. The disadvantages with artificial laser navigation are the cost of the scanners and that the AGV is dependent of the reflectors. Artificial laser navigation is also sensitive to dirt and sunlight since the dirt covers the reflectors and the sunlight disturbs the laser. Artificial laser navigation is the method that most suppliers recommend since it is a well tested technology and has high precision.

A newer laser navigation method is contour navigation. Instead of the reflectors the laser scanner scans the contours of the environment in which it operates. This makes the system more autonomous since it is not dependent on any external equipment. The disadvantage with contour navigation is that around 40 per cent of the operational environment has to stay constant. The method is relatively new and has not been tested in the same way artificial laser navigation has. Advantages with contour navigation is for example that it is not dependent on reflectors. The laser scanner that is used for navigation can also be used as a safety scanner which makes the system cheaper. Reflectors are not needed which decreases the installation time and makes the system more autonomous.

For GPS navigation satellites are used to determine the position of the GPS receiver. The issue with GPS navigation is that a clear line of sight upwards is needed, which is not achievable in an industrial environment. This makes GPS navigation problematic for indoor AGVSs. This can be solved by installing a local positioning radar (LPR) that is used instead of the satellites to determine the position. The issue with using LPR is that the precision of the AGVS is diminished to at the most ±10 cm. GPS navigation is best used outdoors where laser navigation or fixed-path navigation cannot be used because of the environmental aspects.

Beside these different methods it is a possibility to combine different methods and make hybrid versions. Many suppliers offer a combination of artificial laser navigation and contour navigation which is a good alternative until contour navigation is reliable and efficient enough to be used alone.

7.1.1.4 Obstacle avoidance

The question whether to have obstacle avoidance in the AGVS is an interesting topic. Academia and practice differ in their view of the matter. Academia believe that it is an important research topic to make the AGVS more flexible while practitioners think it to be a redundant feature that solves an issue that should not exist in a production facility in the first place. Many users mention the increased process stability and cleanliness in the production, because of the urgency to keep the facility clean in order for the AGVS to work properly, as a positive effect that the AGVS has. Obstacle avoidance is therefore a feature that is neither needed nor wanted in an industrial environment but can instead have advantages in other fields of application.

7.1.1.5 Safety

One of the main arguments for implementing AGVSs is increased safety. There are not any considerable areas of discussion when it comes to how a safety system should be built for an AGVS. All suppliers interviewed for this master thesis use a number of safety features with only slight variations between them. These include safety scanners, emergency stop switches and sometimes mechanical bumpers. Other features that can be added are for example extra sensors that detect obstacles that are above ground, designated danger zones and warning signals for load transfer, horizontal bars and traffic lights in intersections.

There is a regulation for AGVSs called the EN 1525 that should be taken into consideration when deciding on safety features for an AGVS. This regulation is followed meticulously by almost all interviewed suppliers. Those that do not follow it fully compensate with other safety features where the regulation cannot be followed. This regulation, as well as other appropriate regulations for industrial machinery, should be taken into consideration when implementing an AGVS. A thorough risk assessment should also be done to understand the individual risks for specific processes that are automatized. Features that should be considered especially are load transfers and the acceleration process of a Towing AGV. Load transfer can be a dangerous process as some of the safety equipment has to be turned off to make the operation possible. Towing AGVs have a blind spot since there are no sensors between the wagons that notice a person between them.

7.1.1.6 Batteries

There are mainly three battery types that are used for AGVs; lead-acid, lead gel and lithium-ion. All batteries have different features and are good for different types of charging schemes. Lead-acid batteries are heavy and a reliable technology with many years of development behind them. They are the cheapest rechargeable battery per kilowatt-hours of charge on the market but have to be charged in full cycles (i.e. they cannot be charged a couple of minutes here and there). Lead-acid batteries create gas when being charged which can be dangerous. They also need to be filled with water from time to time. Lead gel batteries have similar features as lead-acid batteries but do not create gas and charge faster. Less maintenance is also needed for this battery type as they do not require water. The third battery used in AGVs is the lithium-ion battery. These do not create gas, are close to maintenance free and can be charged in very short cycles. The disadvantage is that they are more expensive than lead-acid and lead gel batteries.

7.1.1.7 Charging

When it comes to charging there are four different schemes; manual battery swap, automatic battery swap, automatic charging and opportunity charging. Manual battery swap means that when the battery has fallen below a certain percentage the AGV is routed to a station where the battery is manually changed to a fully charged one. An automatic battery swap is the same as a manual one but with a machine or another AGV that does the swap. The automatic swap makes the system fully autonomously and usually take less time than a manual swap. A battery swapping station is however expensive and in most cases only a good investment if there is a very large AGV fleet or many shifts. The third charging scheme is automatic charging. This means that the AGV goes and charges its batteries when the battery has depleted to a certain percentage. At this time it stays at the charging station until the battery is fully charged. This method works well if a battery that lasts through the shifts of the day can be used. The AGV can then charge at night and be ready for the next day. If a battery like this cannot be found this scheme can have a significant effect on the number of AGVs needed in a system as time for charging is added to the AGV operation time. Both swapping methods and automatic charging work well with lead-acid and lead gel batteries as they function well when charged in full cycles. The last charging scheme used for AGVs is opportunity charging. Here natural idle time is used to charge and should be used when AGVs have many short predictable stops. Charging stations are located near to the AGVs' stop locations and the AGV will charge while it is waiting for the next task. If planned correctly opportunity charging should not affect the operation or the number of AGVs needed as existing idle time is used. For this scheme a lithium-ion battery is optimal as it is not damaged from only charging small amounts at a time. Some suppliers also use lead gel batteries for this charging scheme but then the minimum possible charging time is increased not to damage the battery.

7.1.1.8 The future

The areas mentioned in this section describe what the AGVS technology looks like today. It is, like discussed in the analysis (subchapter 5.9), hard to predict the future because of the fast technological advances but some conclusions can be drawn from the interviews with the suppliers. The amount of lithium-ion batteries used will increase since the price is decreasing and they have a high energy density. Contour navigation will be developed further and become more reliable and used in more AGVSs. Other areas that will be further developed are 3D obstacle recognition, speech guidance and swarm intelligence.

7.1.2 RQ2 – What AGVS technology should Scania use in its material handling processes?

It is possible to find areas of use for all types of AGVs mentioned in this report at Scania but it is recommended that the company starts with an implementation of Forklift AGVs. These can be Hybrid or Standard Forklift AGVs. They both have advantages and disadvantages to consider but are according to the authors of this report equal for standard operations if sold at the same price. When a pilot has been done with Forklift AGVs other AGV types could be looked into such as Underride AGVs, Towing AGVs and Outdoor AGVs.

Regarding the guidance control system it is not a question of what type to use but rather if it is needed. Almost all of the material transportations at Scania is connected to the company's internal logistics operation system since it has to operate according to the takt time. A guidance control system is therefore required for most processes. The guidance control system is highly dependent on a connection to the WLAN. In an industrial environments there are many factors that disturb the connection such as other frequencies, surrounding materials like iron, and welds. These are factors that are present in many of Scania's facilities and therefore have to be taken into account in an AGV implementation.

When it comes to navigation Scania should principally use artificial laser navigation. This is a reliable and robust technology with high precision that is recommended by most suppliers. Other alternative navigation methods should be used for special cases when artificial laser navigation is not suitable. Contour navigation is another navigation method that is being developed and has high potential at Scania in the future. Today it is however not fully reliable and therefore not considered to be the best alternative for the company's first implementation projects.

Scania should not use obstacle avoidance as it makes the behaviour of the AGVs unpredictable and since it solves a problem that should not be there in the first place. Possible obstacles for the AGVs should instead be removed and by this create a cleaner production facility.

Regarding safety Scania should implement the safety measures recommended by the chosen supplier. A thorough risk assessment should be done to investigate if there are any vulnerable areas in the AGVS's operation and to find out if any additional safety equipment should be added.

The charging scheme and battery should be chosen based on the amount of shifts, the characteristics of the operation the AGVS will be working in and the layout of the facility. Scania has a two shift operation in many of their facilities and will probably not start with a very large AGV fleet which is why a manual battery swap or automatic charging of lead-acid or lead gel batteries is a good alternative. In the case of automatic charging it is recommended that batteries that last through the two shifts are used so that the AGV can charge at night. In case a secure way to handle the charging gases cannot be found lead-acid batteries should not be used. If many natural breaks occur in the operation of the AGVS opportunity charging with lithium-ion batteries is also an option. This is also a good alternative if it is logistically hard to solve how the AGV will get to a charging station that can handle charging gases.

7.1.3 RQ3 – Which are the major factors that decide whether an AGVS is suitable for a material handling process?

The majority of the factors that have to be taken into consideration when implementing an AGVS can be categorised as process specific, product specific and financially specific.

The process specific factors comprise the tasks that the process consists of as well as the environment in which the AGV operates. The complexity of the process and to what extent it can be automatized is decisive for an efficient and profitable AGVS. Complex tasks will either require more AGVs or decrease the throughput of the process, and if not all tasks can be automatized an employee will still be required. Ultimately these factors will affect the return on investment.

Other process specific factors are whether the AGV operates in the same area as manually driven forklifts and humans as well as the conditions of the floor. When the AGV operates in the same area as manually driven forklifts and humans the efficiency and the reliability of the system will decrease since manually driven forklifts and humans will interfere with the AGV's path and cause it to operate at a slower pace. Poor condition of the floor where the AGVS operates affects the AGVs' precision and could by vibrations damage the fragile and expensive equipment on the AGV. It is also important that the floor has a high shear strength since the AGV follows the same path each time it operates in the area and could otherwise cause tracks in the floor.

The product specific factors are the aspects connected to the products that are handled in the process. A wide range of load carriers and product varieties increase the complexity of the process and require a more advanced AGV. Therefore the key is a high level of standardisation for the load carriers and product varieties to achieve an efficient system.

The financially specific factors indicate if a process is suited for an AGVS from an investment point of view. There are many ways in which an AGVS can reduce costs. The most prominent way is as a rationalisation investment and in that way cut costs by relocating employees. The factors that are decisive in these cases are the volume of the material flow, where a higher volume indicates that it is a time-consuming task, and the number of employees that can be relocated. A high volume of the material flow is the leading indicator that a process is time-consuming, but it is not enough to make a good business case. If employees cannot be relocated the AGVS will only lead to increased costs. Because of this the number of relocated employees should be used to measure the profit instead of the amount of freed up work hours. The implementation of an AGVS can potentially lead to further cost savings than the ones gained to further cost savings than the ones gained from rationalisation. The AGVS both increases the quality of a transportation process and the process stability. By eliminating the risk of human error in the transportation the risk for damaged goods and safety hazards decreases and by that also the costs related to these issues. An increased process stability creates an even flow and makes the process, and the connected processes, more stable. This can reduce buffer storages and enable further automatization.

7.2 Limitations

One of the limiting factors for this project has been time. More time could have opened up for the possibility of interviewing more reference companies to validate a larger amount of the supplier information. Reference companies with other types of AGVs than the classical forklift AGV could have been interviewed as well as more than one person from each reference company to get a more complete picture. Additional time could also have been used to interview more suppliers; the question is however if this would have more than marginally improved the results and the credibility of the report. The information gathered from the five interviewed suppliers was often coherent which indicates that other suppliers might have given similar information as well. This can however not be known without doubt.

With more time it would also have been possible to analyse Scania's material handling process further. A more in-depth understanding of the material handling processes at Scania would have made it possible to design the guideline with more details and distinct recommendations. The goal with the guideline was however to make it applicable to Scania on a global scale. A more in-depth understanding would require visits to other production units than the ones in Södertälje in order to keep the guideline general for all of Scania; something that there were neither funds nor time for.

Geographic limitations were also a factor. Because of limited possibilities to travel, suppliers and reference companies in Sweden and northern Europe were in most cases chosen to be interviewed. With the companies chosen outside of Sweden telephone interviews had to be conducted without any onsite visits to see the technology. Even if the goal was to obtain the same amount of information from all the suppliers the telephone interviews made it difficult. On site visits made it possible to see the vehicles in action, which gave a deeper understanding of their technology. The experience and knowledge of the interviewees differed and therefore the amount of information collected differed between the different suppliers and reference companies.

A third limitation was that the report almost exclusively was a qualitative study. To be able to measure the precision of different navigation types for example could have led to more objective results. This was hard since very little data could be found.

A fourth limitation of the report is that no financial calculations were made. This was not done because of time constraints and since they would not have been as accurate as the ones made by the supplier since the total cost of an AGVS is very dependent of the design of the specific process. Even if financial calculations are not within the scope of the project it would have been interesting to get a feeling for the price differences between the different technological alternatives as this can affect an implementation like this severely.

7.3 Future research

Since AGVs is a growing field there are many areas of future research. Since the AGVS technology moves forward at a fast pace a similar study to this one could probably be done in a couple of years with entirely different results. Some future developments have tried to be foreseen in this report but this is of course only possible to a certain extent. A study like this could use this report as a stepping stone.

Another area that could be studied is the best practice for an AGVS implementation with a focus on change management and automatization in a broader perspective. An AGVS implies an extensive change in the process for the employees which inclines a risk of failure during the implementation. A best practice study for how to implement an AGVS could decrease the risk of failure and shorten the implementation time.

A more specific AGV study could be to investigate a solution for how to solve the load transfer problem for Towing AGVs. Today there is no feasible solution for how to solve this automatically without the need for a human.

A final area of future research that was found interesting by the authors of this report but was not researched since it was not within the scope of the study is the connection between AGVSs and lean. Many of the benefits with an AGVS correlates with the Lean philosophy such as removing waste in the form of transportation, creating a more standardised process and creating an even flow. It would therefore be an interesting topic to research an AGVS’s future importance to a lean organisation, and also how important it is that an organisation is lean to successfully implement AGVSs

7.4 CONTRIBUTION TO THEORY

There is a lot of information to be found on AGVs in scholarly articles and books but this information is often very technical and concerns details about how a certain navigation system is tested under a specific condition for example. There is very little information about how AGVSs work in an overall perspective and where they should be implemented. This report has combined information from a great number of sources and is therefore one of a kind in the information it covers. To the knowledge of the authors existing theory has never been combined with information from suppliers, users and the thoughts and input of a future user, in this case Scania. This is what this report contributes to theory.

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9 APPENDICES

9.1 APPENDIX A – NUMBER OF PUBLICATIONS ON AGVS

With the help of Scopus information was gathered regarding how many articles, conference papers, books etcetera have been published from the first publication on the internet in 1974 to 2016. The publications that were taken into account had the phrases "Automated Guided Vehicle" or "Automated Guided Vehicles" in the title, abstract or keywords. The data found can be found in table 9.1.

Table 9.1 - Data regarding number of AGV articles published per year

Year	1974	1975	1976	1977	1978	1979	1980	1981	1982
Nbr of publications	1	0	0	0	0	0	1	1	1
Year	1983	1984	1985	1986	1987	1988	1989	1990	1991
Nbr of publications	33	13	56	71	39	34	33	33	34
Year	1992	1993	1994	1995	1996	1997	1998	1999	2000
Nbr of publications	27	53	55	47	50	58	35	26	37
Year	2001	2002	2003	2004	2005	2006	2007	2008	2009
Nbr of publications	54	48	46	56	66	74	56	74	69
Year	2010	2011	2012	2013	2014	2015	2016		
Nbr of publications	79	78	87	106	91	94	92		

9.2 Appendix B – Interview guide suppliers

Description of purpose of the study and the motivation for interview for the interviewee.

This information is going to be part of a report that will be used by Scania internally but also published on the internet. Is it ok if we publish all the information we have received from you today? We will send you the written text in the report concerning you first for your approval and possible fact checking.

Is it ok if we record this interview?

Introduction

- What is your name and position in the company?
- What is your definition of an AGV?
- There seems to be an increased demand for AGVs during the last couple of years and many think that this trend will only increase. This is interesting since AGVs were first developed during the 50's and the laser technology is from the 90's. Why do you think this is?

Types of AGVs

- What types of AGVs do you produce? (Forklift/Piggyback/Underride/Towing)

If forklift AGVs:

- Are they built from forklifts (with space for a human) or are they pure forklift AGVs (without space for a human)?
- What are the benefits and disadvantages with each type?

Navigation

- What type of navigation technology do you use?
- If laser, how many reflectors does the AGV need to see?
- If optical/magnetic tape, what happens if the magnetic tape is broken somewhere?
- Why have you chosen to work with this/these navigation methods?
- Which navigation method has the highest precision?
- Which navigation method is in your opinion the best?
- How do the technologies differ in cost?
- Which navigation method do you think is suitable for which situations?
- What is negative/positive with the technologies?
- How do you create the map that it navigates with?
- What do you see for the future? (E.g. SLAM and contour navigation)

Obstacle avoidance

- When it comes to obstacle avoidance, do the AGVs recalculate the route or stop?
- If they stop, do they signal this in any way?
- How do they handle an object that is in the way at for example 1,5 m height?

Energy supply

- What type of batteries do you use?
- What are the benefits/risks (fire, gases, etc.) with the batteries you use?
- How long operational time does the battery have before it has to charge?

- What battery is most environmental friendly?
- How do your AGVs charge? Do they work with battery swapping, opportunity charging, automatic charging or combination charging?
- What type of charging is according to you compatible with the different batteries you use?
- Are there any specifications regarding where the AGVs need to charge?
- Would you say that there is a difference between how much energy a forklift and an AGV consumes?
- What type of batteries do you think will be used in the future?

Maintenance

- What type of maintenance is necessary?
- What happens if the AGV malfunctions?
- How does the maintenance compare to a regular forklift?

Safety

- What legislation/guidelines do you base your safety restrictions on? Why these?
- Do you see any problems with today's safety restrictions?
- What safety technology do you use today and what do you see will be used in the future?
- Are there any dead angles that your AGV does not see?

Local environmental aspects

- What factors are critical to look for when wanting to implement your AGVs? E.g. floors, traffic, distance, etc. Why?
- How do your AGVs handle traffic in the same area as they work? Is it possible to have traffic in the area? (Traffic such as other people or manual forklifts)

Guidance control

- Do all your AGVs require a guidance control system?
- What do you think about SWARM?

Actions

- Can they be used for replenishment with boxes or similar? For example shootring.

Other

- What other benefits except safety and cost savings do AGVs have in your opinion? Are there any disadvantages?
- What aspects do you see as decisive when investigating if a process is suitable for an AGVS or not?
- Is there something that we haven't asked that you think is relevant to mention?
- Thank you for your time. We will get back to you with a written summary of the parts of this interview that will be used in our report.

9.3 Appendix C – Interview guide reference companies

Description of purpose of the study and the motivation for interview.

This information is going to be part of a report that will be used by Scania internally but also published on the internet. Is it ok if we publish all the information we have received from you today? If requested we can send you the written text in the report concerning you first for your approval and possible fact checking.

Is it ok if we record this interview?

Introduction

- What is your name and position in the company?

Specifications for the AGVs

- What type of AGVs have you implemented?
- In what type of processes have you implemented the AGVs?
- How many AGVs have you implemented?
- What type of navigation do you use and why?
- Have there been any difficulties with your chosen navigation type?
- What type of energy supply system do you use?
- What type of battery technology have you chosen and why?
- Have you equipped your AGVs with any extra safety equipment except for the standard equipment?
- Have there been any accidents connected to the AGVs?
- How has the safety atmosphere in the production/warehouse changed after implementation?
- Is your AGVS able to avoid obstacles or do the AGVs just stop?
- Do you use a guidance control system to control the AGVs? Is it linked to your ERP, MRP or WMS system?

Usage

- Are your AGVs operating where there are people or other trucks moving?
- If not, why did you decide on this? If yes, how is this working?
- What tasks do your AGVs do?
- What environmental factors have been critical for you when implementing the AGVS? (E.g the condition of the floor, traffic, specific tasks)

Implementation

- Why did you implement AGVS?
- What did you see as the main contribution from the technology?
- What were your biggest areas of concern when implementing the AGVS?
- Are you satisfied with the results from the implementation of the AGVs?
- Have there been any positive effects from the implementation that you did not expect when ordering the AGVs?
- Is there something that was promised by the supplier but has not worked as it was said?
- Have you experienced any problems with your AGVs?
- How has the staff reacted to the implementation of the AGVS?
- What are your key learnings from implementing the AGVS?

- Have you named your AGVs?

The future

- Are you going to implement more AGVs?
- Are there any technical aspects that you will want to change in that case? (E.g. other navigation, guidance control, energy etc.)

9.4 Appendix D – List of interviewees

Table 9.2 - List of interviewees

Type of company	Company	Name interviewee	Title interviewee	Interview topic	Date of interview
Scania	Scania	Lennart Lundgren	Supervisor of this Master Thesis and Logistics Developer at Global Logistics Development	Scania in general	2017-01-19
	Scania	Tina Arnstedt	Senior Manager at Global Logistics Development	Scania in general with a focus on company culture	2017-01-19
	Scania	Åsa Rynninger Eriksson	Logistics Developer at DT (Transmission assembly)	Production flows at DT	2017-01-23
	Scania	Dhawal Patel	Logistics Developer at MS (Chassis assembly, trucks and busses)	Production flows at MS	2017-01-26
	Scania	Saleh Mirza	Logistics Developer at DE (Engine production)	Production flows at DE	2017-02-06
	Scania	Gunnar Granqvist	Business Relationship Manager IT	IT	2017-03-02
	Scania	Thomas Paulsson	Senior Advisor Safety Processes	Safety	2017-03-17
	Scania	Ruthger de Vries	Executive Vice President for Production and Logistics	Scania's strategy "A forklift free production"	2017-04-27
Supplier	Egemin	Noë van Bergen	International Business Development Manager	AGVSs from Egemin	2017-02-09
	Jernbro	Pär Knutsson	Project Manager Sales	AGVSs from Jernbro	2017-02-20
	Toyota Material Handling	Henrik Eriksson	Business Development Manager with focus on automation	AGVSs from Toyota Material Handling	2017-02-21
	Softdesign	Christopher Wessberg	Deputy Managing Director	AGVSs from Softdesign	2017-02-21
	AGVE	Jakob Dannemark	CEO and Co-owner	AGVSs from AGVE	2017-02-22
	DS-Automotion	Markus Gartner	Sales Engineer and System Designer	AGVSs from DS-Automotion	2017-04-05
Reference company	Haldex	Anne Andersson	Shift Leader	Haldex's AGVS	2017-03-06
	Systemair	Anders Westling	Maintenance Supervisor	Systemair's AGVS	2017-04-04
	SKF	Peter Schmid	Demand Change Project Manager	SKF's AGVS	2017-04-06

9.5 APPENDIX E – A GLOSSARY OF THE AGVS TECHNOLOGY

Glossary	
Active Inductive Guidance	A form of fixed navigation where the AGV follows a magnetic field that is created by a conductor inserted in the floor
AGV	Automated Guided Vehicle
AGVS	Automated Guided Vehicle System
Anchoring Point Navigation	A group of navigation methods where the AGV uses dead reckoning and artificial orientation sites in the floor to navigate
Artificial Laser Navigation	A form of open navigation where the AGV navigates by identifying reflectors in the facility with a laser scanner
Assembly AGV	A type of AGV that carries an assembly object on a path where the object is being constructed during the transport
Automatic battery swap	A battery scheme where a machine swaps the battery of the AGV
Automatic charging	A battery scheme where the AGV automatically goes and charges itself when its battery has depleted to a certain level
Contour Navigation	A form of open navigation where the AGV navigates by scanning the environment with a laser scanner
Fixed Path Navigation	A group of navigation methods where the guide paths are physical
GPS Navigation	A form of open navigation where the AGV navigates by a GPS receiver
Guidance control system	The superordinate part of the AGVS that enables communication between the AGVs and handles the transport orders
Heavy weight AGV	A type of AGV that handles heavy loads
Hybrid Forklift AGV	A type of AGV that has forks and space for a human to steer it manually
Hybrid Towing AGV	A type of AGV that tows the load and has space for a human to steer it manually
Manual battery swap	A battery scheme where the AGV's battery is changed manually
Navigation Method	Different methods for how an AGV navigates through the facility
Open Path Navigation	A group of navigation methods where the guide paths are virtual
Opportunity charging	A charging scheme where the natural idle time is used to charge the battery
Optical Guidance	A form of fixed navigation where the AGV follows a painted line on the floor
Outdoor AGV	An AGV type that can be used outdoor
Passive Inductive Guidance	A form of fixed navigation where the AGV follows a magnetic field that is created by an magnetic strip or tape on the floor
Piggyback AGV	A type of AGV with conveyer belts that transfers its load laterally
SLAM	Simultaneous localization and mapping, a technique where the AGV maps it environment simultaneously as it navigates within it
Special Design AGV	A type of AGV that is built completely according to the specification of the customer
Standard Forklift AGV	A type of AGV that has forks and does not have space for a human to steer it manually
Standard Towing AGV	A type of AGV that tows the load and does not have space for a human to steer it manually
The EN 1525 Regulation	The safety regulation regarding AGVSs
Underride AGV	A type of AGV that carries the load on top of it