Evaluating Usage of Automated Guided Vehicles with Respect to Warehouse Layout Changes

A Case Study at Haldex Brake Products

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Abstract

Warehouse operations are considered a key aspect to the success of a supply chain. They are not only costly to the supply chain but they also affect the flow of material both upstream and downstream. Warehouse improvement measures play therefore a considerable role in decreasing cost and lead time by improving material flows. To increase the efficiency of material flows and aiming to reduce labor dedicated to traveling, automated material handling is seen as a key solution. In this regard, production warehouses especially, such as Haldex warehouse in Landskrona seek to invest in Automated Guided Vehicles (AGVs). In light of increased customer demand, Haldex is planning to upgrade its production capacity. The purpose of this study is to evaluate the usage of AGVs with respect to warehouse operations and layout changes. The objectives span from understanding how the layout changes affect material flows, to the evaluation of which flows should be covered by AGVs and finally determining the number of AGVs needed to support the flows. The research is carried out at the selected case company, Haldex Brakes.

The research has shown that as warehouse layout changes, so will the material flows. The increase in customer demand, without adding new storage locations also means that the existing material flows to and from manufacturing processes will become more frequent. The changes in flows were evaluated for AGV suitability based on a set of criteria: suitable storage equipment, distance of the flow, and the level of congestion risk. Based on the criteria, two scenarios were presented. The first scenario is the implementation of three flows which met most the criteria. The second scenario is suggesting flows that can be implemented, following minor changes in the future layout. The number of AGVs needed at Haldex was determined with respect to both scenarios.

To further improve the quality of this research and to develop the topic of automated material flows, it is suggested to perform simulations of the results and how the implementation of AGVs should be carried out. Due to limitations of time and resources, these aspects are not considered in this study.

Keywords: *warehouse operations, warehouse design, warehousing, material flow, automated material handling,* and *automated guided vehicle (AGV)*

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1. Introduction

In this chapter, the background, initialization of the thesis and the case company are explained. The problem faced by the case company is introduced and explains how it motivates this study. Thereafter, the research purpose and questions are presented, as well as limitations to the scope of the thesis.

1.1 Background

Today's supply chains are facing growing pressure as customers are demanding more and more product variety and shorter response time. For most supply chains, warehousing plays a large role in the efficiency of delivering value to the customer. Functioning as storage nodes, warehouses are at the center of the distribution network and are considerably affecting lead time between supplier and customer (Rouwenhorst et al., 2000). Warehouse performance is therefore crucial, impacting service levels, response time and overall cost in the supply chain (Bartholdi and Hackman, 2010). As storage of products is expensive due to requiring time, in terms of handling, personnel, and space, in terms of racks and square meters, warehouse costs are important to control (Bartholdi and Hackman, 2010). In order to improve the efficiency of warehouse operations, a number of areas should considered namely warehouse resources and how they're organized. As such understanding how layout and design affect warehouse operations, is important to achieve a smooth and efficient material flow (Rouwenhorst et al., 2000). An efficient and smooth material flow can be translated into avoiding double handling of material, and identifying and resolving bottlenecks (Bartholdi and Hackman, 2010).

Managing the time it takes to move material is highly relevant to conduct efficient warehouse operations. For example, traveling accounts for about 55 percent of order-picking time (Bartholdi and Hackman, 2010). Aiming to reduce traveling for order picking and other warehouse operations, automation has become more popular, especially in replacing regular industrial trucks with automated guided vehicles (AGVs). Invented in 1953, the technology of AGVs have since then developed from inflexible and expensive to more affordable and flexible in user areas. Using AGVs as a way of handling goods and material is one of the main objectives, as well as creating a more transparent information flow (Ullrich, 2015). By using AGVs, warehouse operations can have increased productivity and reduction in labor costs as an effect of improved material handling and transportation (Ng et al., 2009). In extension, AGVs can reduce the cost of personnel, both in general and by having less personnel dedicated for only movement of material (Ullrich, 2015). AGVs are commonly found in production plants and warehouses that have assembly lines and production cells. This is due to the need of flexibility that AGVs can deliver (Schultze and Wüllner, 2006).

1.2 Company Discussion

Haldex Brake Products AB (henceforth known as Haldex) is a brake production company, with their head office in Landskrona, Sweden. They are operating globally with offices across 18 different countries across multiple continents. They are the global leading supplier of the brake adjusters for drum brake and have currently the fastest growing market share for air disc brakes. As trends are showing a growth of more environmental transportation, Haldex' operating conditions are changing and adjusting to the market. Since they still maintain production and storage in the warehouse in Landskrona, improving warehouse operations efficiency is a key aspect for the global supply chain (Haldex.se, 2018). Environmental transportation is also a focus inside Haldex' production warehouse in Landskrona, where there has been an implementation of automated guided vehicles. The AGVs were bought and implemented in 2013 with the main purposes of increasing productivity, decreasing operating costs and enhancing safety (Pålsson, 2018). These purposes were met by replacing some manual flows of material movement between main areas in the warehouse.

There are two main reasons for the AGVs to be considered for transportation in the warehouse. The first reason is that travel distances between storage locations and different manufacturing processes are relatively long, hence moving material along these flows can be time consuming. The second reason is the flows are high volume and require regular and repetitive movements of material (Hasic, 2018). The focus on transportation for the flows is therefore highly important in achieving a more efficient warehouse. In the past few months, changes in warehouse layout and production processes hindered the appropriate use of the AGVs. A part of the production has been moved to Hungary, freeing space in the production area. This space will be replaced by a coating process, which is currently outsourced to a subcontractor in south of Sweden. The coating process is under construction and is expected to be operating during the first quarter in 2019. In addition to the coating process, the production process will be extended with new machines and a new assembly line will also be implemented during 2019. The changes are to be able to keep up the increase in demand and as such, increase in production volume. A change in ERP systems also affected the usage of AGVs, as the change resulted in having to reprogram routes and orders for the vehicles. The reprogramming has, up to the publication of this thesis, not been made, and the AGVs are as of november 2017 no longer operating in the warehouse.

1.3 Purpose and Research Objectives

As this thesis was initiated by Haldex, is is important that the research carried out aims at presenting solutions to the challenges currently encountered by the company. This research should still be able to provide an understanding about the topic of warehouse operations and management, in the form of a structured and comprehensive study backed up by proven theoretical knowledge. Hence, the purpose of this study is to:

Evaluate usage of automated guided vehicles with respect to warehouse layout changes.

In order to achieve the purpose, three concrete objectives have been formulated. These objectives will attempt to define the overall structure of the research and act as a roadmap in the report. The objectives can be seen if figure 1.1.

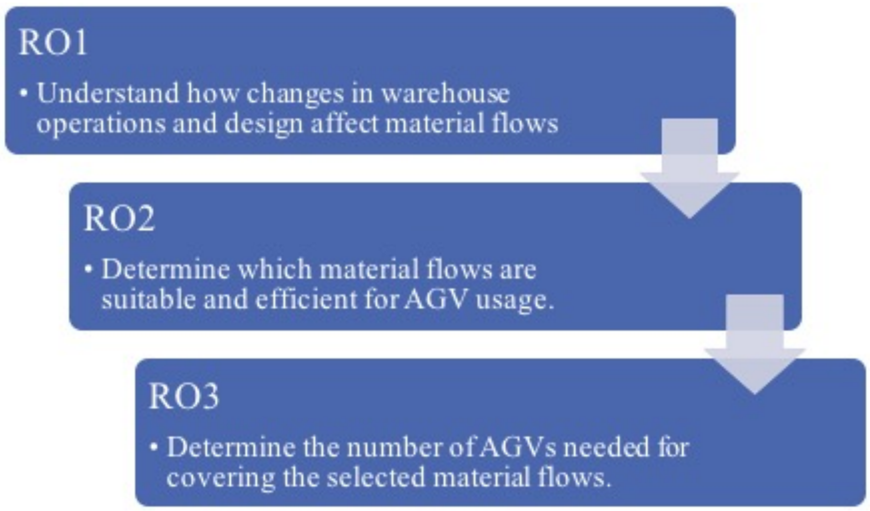


Figure 1.1 Research objectives

Research Objective 1 - Understand how changes in warehouse operations and layout affect the material flow.

As a response to the increase in customer demand and the changes in the market, Haldex has been going through several structural changes both big and small. These changes in production capacities and processes are automatically reflected on logistical operations in the warehouse. Future changes at the Landskrona plant will include adding a new manufacturing process which is coating, purchasing new machines and new assembly lines, in addition to minor changes in the layout. Before evaluating how AGVs can be used to improve internal logistics at Haldex, it is necessary to understand how these changes will impact the material flows. To do that, the current processes and material flows need to be defined and understood in addition to the future changes. Accordingly, a map of the current situation and future situation will attempt to illustrate the warehouse operations and design. The mapping will not only be a tool to illustrate the state of the warehouse, it will also allow a thorough analysis of the future state and an explanation of the resulting material flows.

Research objective 2 - Determine which material flows are suitable and efficient for AGV usage.

By the initiation of this thesis, demand volume is expected to increase and changes in the warehouse layout will most likely affect the travel distances in the warehouse. With all traveling currently carried out by manual forklifts, there is a wish to return to a more automated handling, as was previously done with AGVs before the change in ERP system and processes. The selection of where to use the AGVs during the time they were operating was based upon increasing productivity, decrease operational costs and increase safety.

Both the warehouse operations and layout will change in the near future and so will also the material flows. After understanding how the material flows changes in the first research objective, each flow should be evaluated to identify which of the flows results in efficient usage of AGVs and why. Efficient usage of AGVs will have to be researched and transformed into a set of criteria to use for the selection of flows. Limitations and requirements of the AGVs for warehouse layout aspects such as storage equipment and routing will have to be investigated. Also technical aspects such as connections to ERP or navigation should be covered, especially considering the change in ERP system at Haldex affected the current usage of AGVs. The evaluation of the flows in relations to the developed AGV criteria aims to result in a selection and recommendation of which flows the AGVs should be used for.

Research objective 3 - Determine the number of AGVs needed for covering the selected material flows.
After understanding how the future changes will impact material flows, and which of these flows should be used by AGV, there is a need to evaluate how many AGVs are required to support these flows. To be able to do so, relevant mathematical models supporting this decision should be identified. Understanding how the AGVs function is also important. Relevant information concerning Haldex' previous experience with AGVs, applicable for the second research objective, will apply to this one as well. The expected result of this research objective is to discuss the number of AGVs needed to support the future capacity of the suggested flows from RO2.

1.4 Delimitations

For any study to be feasible, it is important to draw lines and define the scope. This study will focus on the internal logistics, meaning every operation that happens within the walls of the warehouse, as shown in figure 1.2. Unloading, loading and shipping will therefore not be taken into consideration.

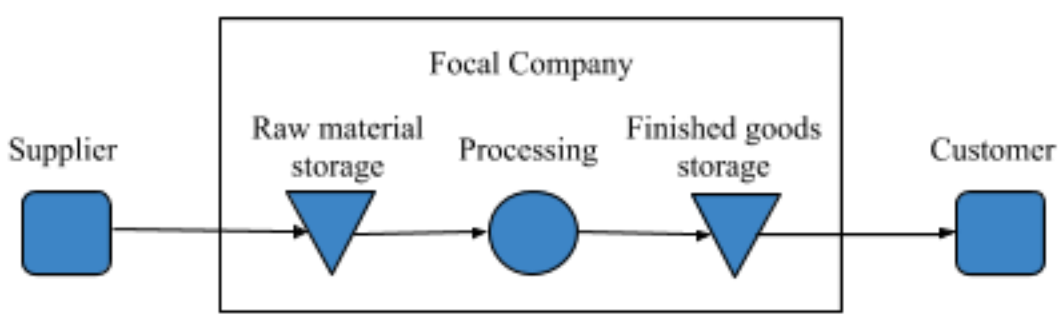


Figure 1.2 Overview of a simple material flow in a company, inspired by Lumsden (2007).

With the scope of understanding how layout changes affects the material flow, theoretical background about warehouse redesign and layout will be looked into. However, as most of the identified literature regarding warehouse design and layout is about structuring new warehouses, some information has to be read inbetween the lines in order to apply it to a redesigning problem. The aspects which will be considered will only be those within the warehouse. Thus, any aspects regarding placement of walls or gates, ceilings, and location will not be considered.

Layout changes in a warehouse is highly connected to change management. While change management is an important topic to achieve a successful redesign process,it will not be considered for this study as it is not in line with the purpose of the thesis. Aspects connected to change management such as motivation of staff, planning and implementation processes will therefore not be covered.

It is desired that the final solution presented to the case company can result in a cost reduction. However, no cost analysis related to the recommendations will be conducted. Any cost cutting possibilities will be presumed and up to the interpretation of the result.

2. Frame of Reference

This section presents the relevant literature that is used as a basis and logic for the empirical findings and the analysis discussion. By interpreting the research objectives, the topics of warehouse operations and design, material flow and AGVs will be investigated as these areas overlap. Presented in figure 2.1 is the relation between the research objectives and the topics.

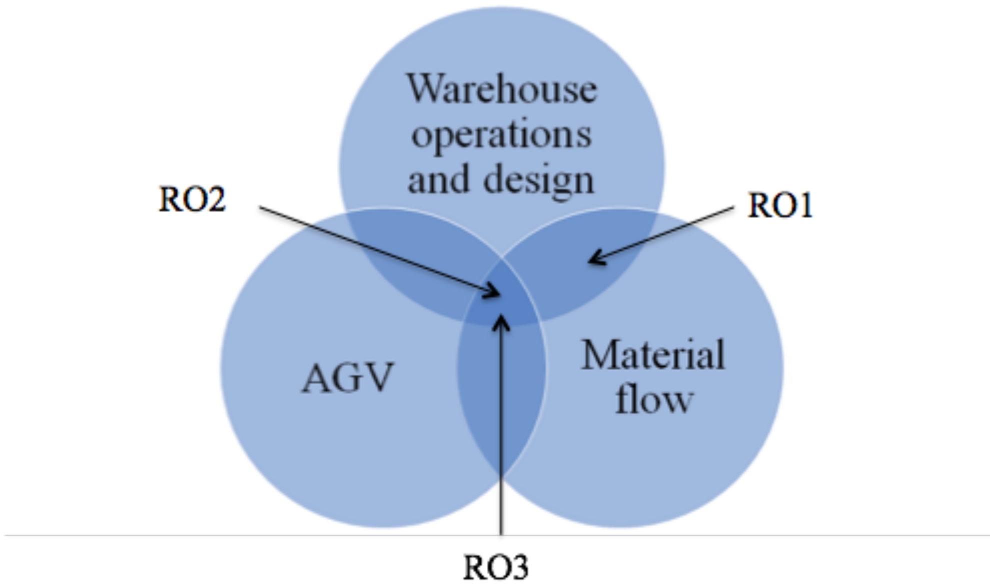


Figure 2.1 Frame of reference and how topics relate to the three research objectives.

2.1 Warehouse Operations

Warehousing is a crucial aspect for the profit of the entire supply chain because it affects both cost and service aspects in the supply chain. One of the main reasons of having a warehouse, besides storing products, is to be able to adapt to quick changes in demand, which could be difficult to handle without the warehouse (Bartholdi and Hackman, 2010). As warehouse operations can vary, there is a need for different set ups and types of warehouses. Van der Berg and Zijm (1999) distinguished between contracted, distribution and production warehouses, the characteristics for each type are shown in Table 2.1.

Table 2.1 Classification of warehouse types and the characteristics (developed from van der Berg and Zijm, 1999; Rouwenhorst et al., 2000).

Warehouse Type	Characteristics
Contracted Warehouse	An external partner, typically with one or more customer, is performing the warehouse activities.
Distribution Warehouse	Products from different suppliers are consolidated and delivered to customers. Can include value-adding activities such as assembly or kitting.
Production Warehouse	Storage of material for production process. The storage typically includes raw material, work-in-progress and finished goods.

While the warehouses characteristics might differ slightly between different types of warehouses, the warehouse operations can be generalized and applied to each type with slight modifications (Bartholdi and Hackman, 2010). The main warehouse operations are visualized in Figure 2.2. It can be noted that warehouses might have different processes for the same operation. In the case of companies handling return flows for example, the operation of receiving can be done according to two different processes. Products are handled differently depending on whether they are received from a supplier or returned by a customer.

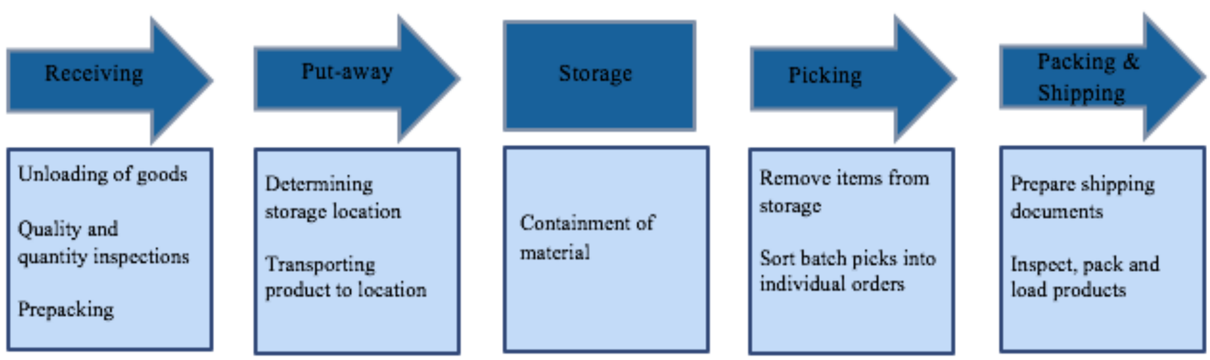


Figure 2.2 Warehouse operations and related activities (inspired and developed from Bartholdi and Hackman, 2010; Gu et al. 2007)

Following the forward flow of material, the first operation is receiving. In this operation, goods are unloaded, typically in a designated receiving area of the warehouse, waiting to be processed. The receiving can also include quality inspections, such as looking for damaged goods or quantity confirmation (Tomkins et al., 2010). Another activity which can take place in the receiving operation is the pre-packing of goods to simplify the following warehouse activities (Frazelle, 2002). The activities included in the put-away and storage operations are viewed differently by different literature works. Bartholdi and Hackman (2010) states that the determination of where an item should be located and the transportation to that location is carried out during the put-away process. Van der berg and Zijm (1999) and Gu et al. (2007) on the other hand discuss that determining the storage location and transporting the item, including the actual storage of the item, are done during the storage process.

Order-picking is considered the most costly warehouse operation, accounting for approximately 55 percent of total warehouse operating costs (Bartholdi and Hackman, 2010). As traveling makes up for such a large part of the costs, automating this process can be highly beneficial in terms of time savings, for example with the use of automated guided vehicles (Bechtsis et al., 2017). The activities in this operation include removing the items from storage and sorting batch picks into individual orders (Frazelle, 2002: Gu et al., 2007). It also includes a large amount of traveling and searching for the location, where traveling is estimated to take up 55 percent of the total order-picking time (Bartholdi and Hackman, 2010). Frazelle (2002) and Gu et al. (2007) on one hand consider preparing shipping documents, packing and performing quality checks as part of the packing and shipping operation. Bartholdi and Hackman (2010) on the other hand separate the two with first performing checking and packing as one operation and shipping as a different operation.

2.1.1 Internal Logistics Systems

Warehouse operations are typically tracked and recorded using a computer software (Bartholdi and Hackman, 2010). The software can be classified as either a Warehouse Management System (WMS) or Enterprise Resources Planning (ERP) depending on the company's activity scope (Legutko, Staniszewski and Milej, 2012). ERP is a system that includes all production and distribution processes of the organization. It incorporates all the different functions related to the company's activity to make the flow of information easier and faster (Legutko, Staniszewski and Milej, 2012). ERP systems are intended for service and production companies. WMS is a software tool specialized in supporting all technical warehouse operations. WMS is either an independent system used by logistics companies or part of an ERP system (Legutko, Staniszewski and Milej, 2012). ERP or WMS have become an important warehouse organization tool. Nowadays, It is not only used to record warehouse transactions for the purpose of managing financial transactions but also to support warehouse operations. These systems are now able to locate stock real-time and direct picking and put-away operations (Bartholdi and Hackman, 2010).

2.2 Material Flow

Material flow is the physical movement of materials from a source to a destination across the supply chain. The goal of every supply chain is the coordinated and continuous flow of material from the raw material supplier to the end customer (Harrison, 2002). A material flow that is not continuous and synchronized could lead to unnecessary use of resources, double handling, and additional space, and thus increase warehousing operational costs (Bartholdi and Hackman, 2010). Optimizing material flows can have benefits such as decreasing levels of inventory and inventory investment costs (Arnold et al., 2008). Hence, the efficient management of material flows can lead to a more efficient use of the company's resources (Arnold et al., 2008).

Material flow in manufacturing environments is defined as *"the organized movement of material from point X to point Y in the entire production system"* (Alvarado-Iniesta et al, 2013, p. 4785). This definition concerns the movement of material inside the confinements of a plant. The flow is considered the most important factor in a production system as optimizing it can directly lead to reducing operation costs. Material flow in a production warehouse is subject to moving three types of materials: raw materials, work in process and a finished product (Bellgran and Säfsten, 2010). This movement should be organized in a way to transport the materials to the intended receiver or location with the right amount and at the right time (Bellgran and Säfsten, 2010).

In complex manufacturing environments, explaining or tracking the material flow can be difficult to do without graphical tools. Material flows can be illustrated using process flowcharts or other types of mapping tools. Process flow analysis allows for documenting activities graphically and in a detailed manner (Bellgran and Säfsten, 2010). The steps of process flow analysis is identifying and organizing processes and activities, documenting the whole process, performing an analysis of the process and identifying possible improvements. A process flow analysis can also be seen as a way to simulate the future state of the system (Bellgran and Säfsten, 2010).

2.3 Warehouse Design

Warehouse design is seen as one of the core decisions in warehousing. It involves determining the layout and selecting equipment that satisfy a predetermined functional description and technical specifications. Warehousing operations, material handling and facility layout are three fundamental elements that are taken into account when defining the specifications (Rouwenhorst et al., 2000). The goal of warehouse design is to achieve smooth and cost-effective warehouse operations (Dowlatshahi, 1994). Dowlatshahi (1994, p.1313) highlights the importance of incorporating the three elements in the design phase of the warehouse and states that "*facilities design, and its components such as plant layout, warehousing and material handling equipment, has been viewed (...) as the costly evils required of the operations of the entity*".

2.3.1 Warehouse Layout

The layout of a warehouse is the detailed configuration within that warehouse (Gu et al., 2010). The layout configuration decisions include storage locations, locations of receiving and shipping, aisle configuration and space. Storage locations choices naturally depend on warehouse operations. However, it is agreed that products should be stored in the most convenient locations; saving both labor used to store or retrieve them and the space they occupy while in storage.

Locations of receiving and shipping also play a part in having convenient locations (Bartholdi and Hackman, 2010; Gu et al., 2010). Receiving and shipping docks are usually put in the same direction as the material flow and aisle direction such as shown in figure 2.3. The shading in the figure illustrates very convenient locations in a darker shade and less convenient locations in a lighter shade. This way, more convenient locations are created than if the dock would be placed in the right side of the warehouse instead. As a result, travelling time is saved during picking and put-away operations (Bartholdi and Hackman, 2010). The space allocation for both storage equipment and aisle width both influence the choice of material handling equipment. In some cases, the choice of material handling equipment comes first, therefore affecting the choice of the size of lanes and rack equipment. When it comes to space saving, an another decision to be taken is whether storage should be centralized meaning grouped in one location or decentralized which means spread out in different locations in the warehouse (Gu et al., 2010).

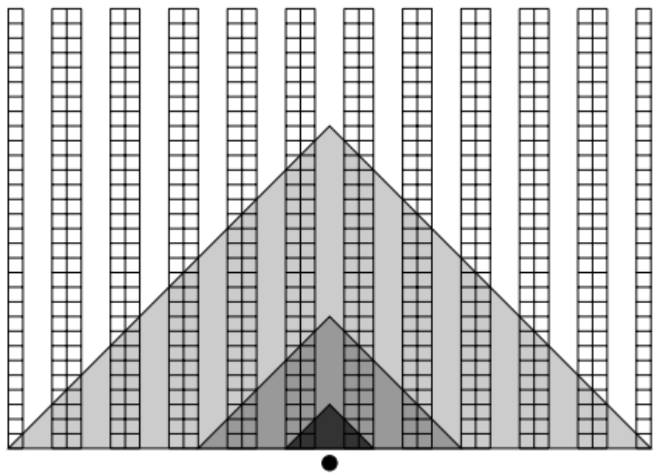


Figure 2.3 Example of warehouse layout where location of receiving and shipping dock placed in the same aisle direction and resulting convenient locations (Bartholdi and Hackman, 2010).

2.3.2 Storage Equipment

In warehousing, materials or products are handled and stored using different handling units. There are typically three types of storage handling units discussed in the warehouse literature: pallet, case and piece (Bartholdi and Hackman, 2010). Pallet is the biggest unit size and is the most commonly used in warehouses, upstream in the supply chain. As products move down the chain, they are usually broken down to smaller units such as cartons and pieces (Bartholdi and Hackman, 2010).

Storage equipment should be chosen to match different handling units. Gu et al. (2007) discusses two main issues for selecting storage equipment. The first one is the identification of which equipment alternatives are reasonable for the requirement of the SKUs and/or products being stored. The second issue refers to how, after solving the first issue, to choose which of the alternatives to use (Gu et al., 2007). Choosing the right storage equipment is an important decision as it can contribute to efficiency in material handling and by that reducing labor costs. Storage equipment can also be used in a way to save space and increase warehouse space utilization. The benefits of storage equipment, as discussed by Bartholdi and Hackman (2010), are summarized in Table 2.2.

Table 2.2 . Benefits of storage equipment (Bartholdi and Hackman, 2010).

	Reduce labour cost	**Increased space utilization**
Storage equipment	Increased pick density by allowing multiple SKUs on the pick face, thus increasing number of picks/person	Ability to store products high and utilize less floor space
	Improved product handling, picking and/or restocking made more efficient	Creating subregions in the warehouse by partitioning, making packing more dense

The easiest way of storing unit loads is to put the pallets directly on the floor, arranged into lanes (Bartholdi and Hackman, 2010). However, as SKUs have to be assigned an individual lane in order to avoid mixing up the SKUs, a lot of space goes unutilized (Kay, 2012). To increase space efficiency in a warehouse, storing in racks is recommended. The racks enables bulk storage and full-case picking. Commonly used racks in warehouses can be single deep, double deep, flow-through, drive-in/through or push-back racks (Hackman et al, 2001). Characteristics, advantages and disadvantages of each of the types are displayed in table 2.3. The most straightforward storage type is the single-deep and the double-deep racks, where the double-deep is two single-deep racks placed back to back. Each pallet can be independently accessible in the single-deep rack, while each SKU should be assigned a single lane for the double-deep rack. If not stored in one lane, there is a risk of double handling to remove the inner SKU, however, the risk of unitized pallet position is higher (Bartholdi and Hackman, 2010). The push-back rack have the same disadvantages as the double-deep, but can typically store 3-5 pallets deep. However, there is commonly fewer aisles required with push-back racks (Koster et al., 2007).

Table 2.3 Different kinds of pallet storage equipment with advantages and disadvantages (Bartholdi and Hackman, 2010).

Rack type	Information	Advantages	Disadvantages
Single-deep rack	One pallet deep racks.	Pallets are independently accessible	Requires relatively wide aisle space
Double-deep rack	Two single-deep racks placed back to back.	Fewer required aisles used in the warehouse	Risk of double handling if SKUs are not stored in a single lane Risk of unutilized space if SKUs are stored in a single lane Slightly more work to store and retrieve pallets
Push-back rack	Extension of double-deep rack, commonly 3-5 pallet positions.	Fewer required aisles used in the warehouse	Risk of double handling if SKUs are not stored in a single lane Risk of unutilized space if SKUs are stored in a single lane.
Drive-through rack	Allows forklifts to drive within the rack frame. Pallets are placed in one end and retrieved from the other, using the FIFO-principle	Practical for fast moving goods. Picking and putaway can be done without interference of each other.	Only one level possible, thus viewed similarly to floor storage Risk of double handling if SKUs are not stored in a single lane Difficult to navigate within the frame
Flow-through rack	Slanted shelvings, using gravity to pull down pallets. Using the FIFO-principle with unloading goods in the back and retrieving in the front.	Practical for fast moving goods. Picking and putaway can be done without interference of each other.	Risk of double handling if SKUs are not stored in a single lane.

Given the requirement in a production warehouse for fast flowing units, the drive-through and flow-through rack (figure 2.4) is an efficient storage system to use (Kay, 2012). Especially considering the racks are using the first-in-first-out (FIFO) principle (Bartholdi and Hackman, 2010). With the drive-through rack being limited to only floor storage, the flow-through rack is more efficient if there is a higher requirement in pallet positions (Bartholdi and Hackman, 2010; Kay, 2012).

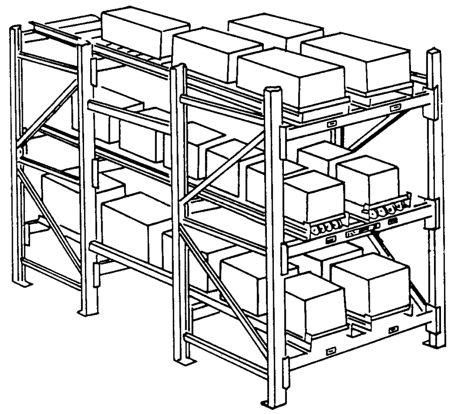


Figure 2.4 Pallet flow-through rack (Kay, 2012).

2.3.3 Storage Allocation

The storage allocation has major impacts on the warehouse operations, processes, and layout, thus it is crucial to make a strategic decision. Literature covering storage location assignment problems (SLAP) are mainly based on the assumption that the material flow in the warehouse is static over the planning horizon. However, the SLAP should be adjusted to dynamic material flow, as seasonality of life cycle may affect the changes in material flow (Gu et al., 2007). Storage locations in a warehouse can be both fixed or mobile locations, for example part of a rack and the forks of forklift, respectively (Bartholdi and Hackman, 2010).

Literature suggests different classifications of storage allocation strategies, but are mainly divided into three areas: shared, dedicated, and class-based (Bartholdi and Hackman, 2010; Reddy Muppani and Kumar Adil, 2008). Other names for shared and dedicated policies are random and fixed policies, respectively (Cormier and Gunn, 1992). In a class-based storage policy, specific regions in the warehouse are reserved for the different classes in which the products are divided into. Both dedicated and shared storage policies are extensions of the class-based policy. With dedicated storage, products are, as the name implies, dedicated to a specific storage location in the warehouse, only to be used by that product. In a shared storage policy however, products can be stored anywhere in the storage area (Reddy Muppani and Kumar Adil, 2008). A shared storage policy uses space more efficiently than dedicated storage. The shared policy is also beneficial when the warehouse contains few number of SKUs (Petersen et al., 2004). While literature studies state that using a shared policy can save travel time, and as such reduce travel cost, it is not always the case. In order to use a shared policy efficiently, one must have a functioning and efficient WMS (Rouwenhorst, 2000). As a result, the downside to using a shared policy is that the staff are not able to learn the positions without a WMS, and as such travel time will not be reduced (Bartholdi and Hackman, 2010).

To avoid issues related to only having one storage allocation policy, many warehouses combines the different ones. SKUs with a class-based policy can for example have dedicated zone based on popularity, but SKUs can within the zone be placed using a shared policy. The policies can also be allocated to different types of SKUs. A typical use is to have a dedicated policy in a forward pick area in order to facilitate picking and to use a shared policy for a reserve area for space saving (Cormier and Gunn, 1992).

2.3.4 Material Handling Equipment

Material handling connect subprocesses in a production system. Material handling and transportation is highly related to creating an efficient material flow in the warehouse. Accounting for 30-70 percent of an items total production cost, the manufacturing and distributing operations affects how products turn into profit (Kulak, 2005). With transportation of material corresponding to 55 percent of the order picking process, the selection and usage of material handling equipment is of great importance (Koster et al., 2007). Different kinds of forklifts can be used to transport and handle pallets, being the most common handling unit, in a warehouse. Forklifts and other industrial trucks are more flexible than conveyors or cranes, as the trucks can move more freely around the warehouse (Kay, 2012).

Table 2.4 Truck types with advantages and disadvantages (Kay, 2012; Bartholdi and Hackman, 2010).

Truck type	Advantages	Disadvantages
Counterbalanced (CB) lift truck	Most versatile type of lift truck.	Wide aisle width required.
Reach truck	Less aisle width required than CB	Typically less loaded weight than CB.
Narrow-aisle reach truck	Fits narrow aisles.	Typically less loaded weight than CB.
Turret truck	Can be used in very narrow aisles due to a turret which can turn 90 degrees.	Narrow aisle requires guidance in forms of tape, rails or wires. Only possible for very flat floors and single-deep racks. Difficult to handle outside rack.

Displayed in table 2.4 are the most common types of trucks being used in a warehouse. The counterbalance truck is the most versatile truck, as it can be modified to fit the requirements in the warehouse. However, it also requires the widest aisles compared to the other types of trucks. Reach trucks are also very common, but can typically handle less load weight than CB trucks.

What kind of truck should be used in the warehouse can depend on different characteristics and warehouse layout, such as aisle configuration and type of storage equipment (Kay, 2012; Bartholdi and Hackman, 2010).

Another way of handling material is to automate the handling and transportation process. This can be done by introducing semi to fully automated solutions (Ng et al., 2009). Semi-automated handling equipment still requires an operator, such as a Man-on-board automatic storage/retrieval system (AS/RS) (Kay, 2012: Bartholdi and Hackman, 2010). With traveling being the largest labor cost in a warehouse, a fully automated handling equipment solution can be desired (Kay, 2012). Fully automated guided vehicles are explained in more detail in next section (2.4).

2.4 Automated Guided Vehicles

Automation of transportation is considered a key aspect in optimizing intralogistics (Schulze and Wüllner, 2006). Automated guided vehicles (AGVs) are used when discussing automated transportation between different units and/or areas in a warehouse or production facility. (Schulze and Wüllner, 2006). Developed in the early 1950's, the idea of the AGV was to automate long-distance round-trip shipping operation in a factory using a tractor trailer (Ullrich, 2015). The technology has since developed and the applications of AGV as well. Transforming from ideas and implementation of the AGVs, the technology has over the years transformed into more innovative approaches and finding new areas of applications (Ullrich, 2015).

An efficient material flow is highly dependent on the transportation between units and areas in a warehouse, therefore, automated guided vehicles (AGV) should be considered. AGVs have high individuality and flexibility, and can therefore be modified to fit to predetermined strategies, such as fitting and understanding storage or routing strategies (Schulze and Wüllner, 2006). If used correctly and efficiently, AGVs can result in economic, environmental and safety-related benefits. The benefits are results of increased productivity and safety, as well as decreased labor costs (Bechtsis et al., 2017). The view that automation leads to a decrease of job availability is often brought up in relation to the implementation of AGVs. However, Schulze and Wüllner (2006) argues that the automation instead will instead assure qualified jobs in the industry.

2.4.1 The Forklift AGV

There are different versions of AGVs on the market, ranging from manual vehicles operated by humans with additional automatic functions to fully automated driverless vehicles (Bechtsis et al., 2017). Depending on what type of unit load is being handled in a warehouse, different versions of the AGV are applicable. When looking at which AGVs are fitted for performing the transport of pallets, Forklift AGV and Piggyback AGV are the best suited options (Ullrich, 2015). While the Piggyback AGV is limited to only one transfer hight and without fork for high level storage, the forklift AGV is better suited in a warehouse which uses multi-level racks.

There are two types of forklift AGVs: specially designed forklift AGVs (Figure 2.5) and the forklift AGV as automated serial equipment (Figure 2.6). Specially designed forklift AGVs can be used independently or in relation to other AGVs by a guidance control system, but has no room for a manual operator on it. The AGV can operate simple task such as straight forward transportation or more complex activities such as taxi operations. The benefits of using a specially design AGV is that there is a possibility for optimal integration on all additional components. It is as well designed for permanent use, including extended service life and accounts for an automatic-compatible energy concept (Ullrich, 2015). The forklift AGV as a serial equipment on the other hand is an extension and enhancement of an standard forklift, with room for an operator if necessary. As the AGV is an enhancement of a standardized forklift, it can be developed from a manufacturer's standard range. Typically, the AGV should be enhanced with safety equipment, guidance, and navigation components as well as sensors for the necessary parts of the AGV. By using a serially produced AGV, cost savings can be made through serial manufacture. Another benefit is proven service and replacement of parts from the manufacturer. Both forklift AGVs are able to perform task such as floor-level load pickup, picks from various heights, handle and stack different kinds of pallets (Ullrich, 2015). When using AGVs, most of the standard issued AGVs have to slow down and scan in order to pick up floor stored pallets, and as such prolong the total operation time for picking and put-away (Ullrich, 2015).

Figure 2.5 (Left) Specially designed forklift AGV (Ullrich, 2015).
Figure 2.6 (Right) Forklift AGV as serial equipment (toyotamaterialhandling.com, 2018).

2.4.2 Technological Aspects

Without the proper technology, the AGVs cannot function. In order for the AGVs to operate according to an industry grade of accuracy, repeatability and reliability, there is a need for a precise guidance control system (GCS) and developed navigation systems (Martinez- Barbera and Herrero- Perez, 2010). When setting up the AGVs, a map needs to be created. The paths and all task points for the AGVs need to be included in the map (Ullrich, 2015).

For the AGVs to function in a more complex situation besides only following a predetermined route, a GCS (figure 2.7) has to be able to communicate with the internal logistics operating system, such as for example a WMS or ERP. Using a WLAN connection, the GCS is able to communicate with the AGVs and peripheral equipment in the warehouse such as for example barcode scanners to determine where the AGV is needed (figure 2.7).

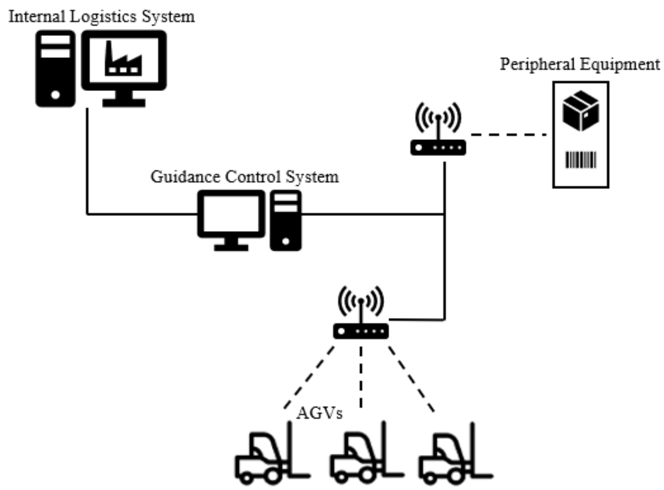


Figure 2.7 The connections of a guidance control system.

For an AGV to carry out an order transport, three processes has to done in the GCS:

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

In the first process, the order is received and prioritized, while continuously checking for feasibility. Once the order is ready to be executed, the internal logistics system is updated and a vehicle dispatch order is sent out. Deciding which AGV should perform the order can be done in different ways, either picking an available AGV at random or to check for an AGV that have the most optimal route to and from the task which is to be carried out. After selecting the AGV to be dispatched, the vehicle fulfills the order and either return to a waiting area och to a changing station after completing the order, unless a new order has been assigned. During the last process, the path and activities along it is planned, this ensures efficient and problem-free movement (Ullrich, 2015).

To fulfill the designated tasks, the AGVs navigates through the warehouse by a navigation system. Two types of navigation systems is mentioned in literature: fixed-path navigation and open-path navigation (Bechtsis et al., 2017; Martinez- Barbera and Herrero- Perez, 2010;

Ullrich, 2015). In a fixed navigation system, the AGV must follow a certain path with the help of physical guidelines on or underneath the floor (Ullrich, 2015). Common applications for this is to use tape, laser markers or wires (Bechtsis et al., 2017). The paths are predetermined and modifications to the path can only be done when the system is shut down and manually change the indicators (Martinez- Barbera and Herrero- Perez, 2010). A more flexible indicator, compared to for example tape, is to use radio frequency identification (RFID) tags (Ullrich, 2015). RFID tags is however more commonly used in a open-path navigation system. Also being known as free-ranging path, the navigation system has no physical guide attributes. To navigate in an open-path system, the AGVs can use, besides RFID, laser guidance, magnet spots or GPS (Bechtsis et al., 2017). As the aim of using AGV is to improve efficiency and flexibility, obstacle avoidance is a large part to consider. Different navigation systems uses the obstacle avoidance if different manners. By communicating with the GCS, the navigation system can either stop or go around the obstacle, depending also of the type of AGV being used. When the AGV is operating within the same areas as manual forklift and pedestrians, the safety aspect of obstacle avoidance is crucial (Ullrich, 2015).

Different kinds of AGVs use different kinds of batteries, requiring different charging methods. The three most common charging methods is charging traction batteries, non-contact energy transfer and hybrid systems. When the AGVs require charging, there is according to McHaney (1995) five methods of charging schemes. The first one, and the most basic, is to manually swap from a dying battery to a new one by ordering the AGV to a charging station. The second method is to use the same approach as the first method, but letting the swapping of batteries by done by a machine instead of manually. In the third methods, the AGV are charged during its natural idle time, placing charging station close to natural stopping points. The fourth method should be used when there is little opportunity for charging and using non-predictable routes. The AGV will operate until it reaches a certain procental limit and is then order to charge at a station until the battery reach an acceptable level. The final method is a combination of the third and fourth method. The AGV can either charge at opportunity until the battery reach an acceptable percentage, or to be ordered to a charging station when it reaches below the determined limit (McHaney. 1995).

2.4.3 AGV System Design

When it comes to the operational level, AGV systems can provide clear advantages in improving material flow. According to Ujvari and Hilmola (2006), AGV systems provide flexibility when it comes to the use of floor space and paths for material flow. They also contribute to flexibility in manufacturing and assembly processes if they are used to move work in process between manufacturing machines and assembly lines for example.

The achievement of these advantages depends on a number of decisions concerning the AGV system and how efficiently these decisions are implemented. In this regard, three AGV system design issues have been identified by Mantel and Landeweerd (1995): track layout, number of AGVs required and operational transportation control. A track layout is the guideline paths or routes that will be used by AGVs in the warehouse. When it comes to designing the track layout, both path-restricted and free-ranging AGVs need a well-designed path. For the path-restricted type, it is natural to design the track layout as these only operate with pre-set routes. Track layout design will not only determine these set of routes but it can also, if designed properly, help limit congestions. Although it may not seem necessary, this decision can also be useful for free-ranging AGVs. Even though this second type is designed to move without pre-set network of routes, designing the track layout can help limit the possible routes. This will reduce route distances and facilitate the control of traffic. There is a conventional method when designing and configuring routes, as the Mantel and Landeweerd (1995) called it, which presents routes as shared among the vehicles in the system. As this method can be complicated both for the design and control of the system, another method has gained popularity because of its route simplification: tandem configuration. Tandem configuration is composed of individual loops for each vehicle meaning that their routes do not intersect. The disadvantage found for this method is it may require more AGVs than in the conventional method as the routes might not be used in the most efficient manner. However, it presents the advantages of avoiding congestions and more simplicity when calculating the number of AGVs needed (Mantel and Landeweerd, 1995).

Mantel and Landeweerd (1995), Ujvari and Hilmola (2006) and Koo, Jang and Suh, (2005) have highlighted determining the number of agvs needed as one of the most important parameters in AGV system design. Ujvari and Hilmola (2006) summarize factors affecting the number of vehicles decision in figure 2.8. The figure shows that layout flexibility has a negative relationship with AGV travel distance and with the number of AGVs. That is because the less the distance travelled by AGVs the less amount number of vehicles needed. Arrival rate of loads is another important parameter. The number of AGVs increases with both the number of transportations tasks and its variability. Ujvari and Hilmola (2006) underline that demand variability is an important factor to consider when calculating the capacity needed for AGV transportation.

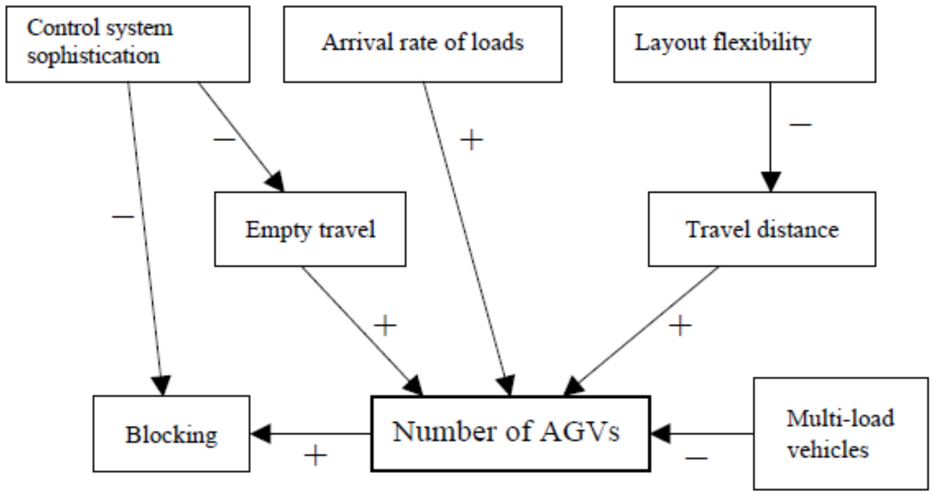


Figure 2.8 Factors affecting the number of AGVs needed (Ujvari and Hilmola, 2006).

The third issue in AGV system design is operational transport control, which is split into two types of control: job control and traffic control. Job control is the organization of transportation tasks assigned to AGVs, also called dispatching rules. It is about overlooking how tasks are scheduled and what routes to be assigned to which AGVs. Traffic control, however, serves to lay traffic rules. An example can be that the AGV that comes from the right side in an intersection should be the one to go first (Mantel and Landeweerd, 1995).

To calulcate the the number of AGVs required in a system; the total loaded time, the total travel time, and the total waiting time of the AGVs during a busy time period, are divided by the total time an AGV is available during that period (Mantel and Landeweerd, 1995). The fleet sizing model by Koo, Yang and Suh (2005) is a mathematical model to calculate the minimum number of AGVs required with the goal of minimizing task waiting time. The objective of the model is to determine the total vehicle travel time given a planning horizon. The total travel time includes the loaded travel time, the empty travel time, as well as loading and unloading times. The model assumes that delivery rates between pickup and delivery stations, within a given period of time, are known. The exact times and places of transportation requests, on the other hand, are not needed for the calculations. The variables used in the model are the following (Koo et al., 2005):

- Number of pick-up/drop-off locations
- Number of vehicles
- Vehicle utilization
- Delivery request rate from pickup location to drop-off location
- Vehicle travel time from pickup location to drop-off location
- Sum of loading and unloading time
- Delivery request rate between all location

The first part of the fleet sizing procedure is to calculate the mean and variance of the loaded travel time and the mean and variance of empty travel time (Koo et al., 2005). Loaded travel can be calculated directly and is independent of the AGV control system setup. At this stage, the minimum number of vehicles can be determined. Empty travel time was said by Ujvari and Hilmola (2006) to be an important factor in deciding the number of AGVs needed. It is a result of the AGV operational control system performance, in terms of vehicle dispatching rules. The more sophisticated the task assignment system the more empty travel time will be reduced. Therefore, before trying to calculate empty travel time, the selection rules the system relies on to assign vehicles to tasks need to be defined. In their model, Koo et al. (2005) define four different selection rules: random vehicle selection, longest idle vehicle or least utilized vehicle selection, nearest vehicle selection and farthest vehicle selection.

The random vehicle selection, whereas the name implies, the vehicle assigned the new task is chosen using randomly and therefore the vehicle could be busy or idle. Thus the probability of the chosen vehicle to finish the task on hand to drop-off location and be assigned task from pick up location is calculated by multiplying the proportion of delivery requirements to destination location with the proportion of delivery requirements from origin location (Koo et al., 2005). Empty travel time can also be found by calculating the net flow at pickup and/or delivery station (Maxwell and Muckstadt, 1982). The net flow being the difference between the total number of unit loads delivered to a station and total number of unit loads picked up from the same station. It accounts for the number of trips to and from that station. After empty travel time is found, the total travel time and the vehicle travel time utilization can be calculated. The fleet sizing model by Koo et al. (2005) suggests an iterative procedure where assignment waiting time is calculated to see if the waiting time is proper. If it is not appropriate, one more AGV is added and empty travel time and assignment times are calculated again until part waiting time is appropriate with the given fleet size. This model however does not discuss an issue that is relevant in choosing the number of AGVs required and that is blocking. Blocking time is when an AGV is blocked by congestion while travelling either loaded or empty (Askin and Standbridge, 1998). The number of AGVs in the system is a factor of congestion and blocking, since the higher the number of vehicles the higher the risk of congestion. The traffic control and routing both play a role in controlling congestion. Authors including Mantel and Landeweerd (1995); Ujvari and Hilmola (2006) have discussed that AGV blocking time is complex to calculate in advance as it is a factor of the AGV systems design. Blocking time is also a factor of the number of vehicles in the system and it is thus not possible to predict before deciding on the fleet size (Askin and Standbridge, 1998). A study conducted by Koff (1987) suggested that blocking time accounts for 10 to 15 percent of the total loaded travel time.

2.5 Framework for Analysis

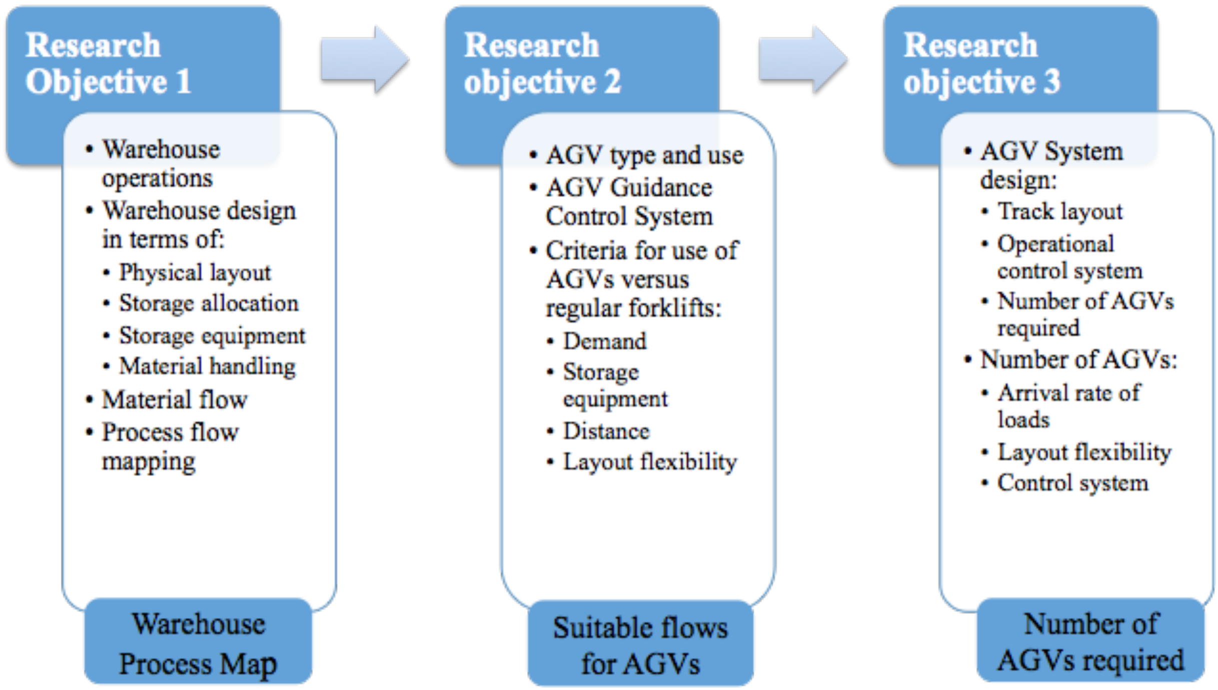


Figure 2.9 Framework for Analysis

The role of the framework for analysis is to link frame of reference findings with the study results and analysis in way to fully address each research objective. The first research objective will be answered based on findings from the first three sections of the frame of reference. In an attempt to understand and map the current and future state of the warehouse, warehouse operations, warehouse design and material flows should be understood. Literature identifies five different warehouse operations: receiving, put-away, storage, picking and shipping. The first step in answering the research question will be to identify and describe how each of these operations are done at the case company. The second step is to determine the warehouse design and its components. The layout is the first components where aisle and space distribution will be explained. Then, the types of storage equipment and the storage allocation will be described. Finally, material handling equipment as it is used should be evaluated. Understanding the warehouse operations and design will provide a comprehensive basis to identify the material flows in the warehouse and map them. The outcome will be to constitute a warehouse process map for both the current and future situation.

The second research objective is about identifying which flows suitable for an AGV system. Included in the objective is also to understanding the types of AGVs, how they are operating in terms of guidance control system and their system design. Warehousing will be used as a foundation to determine the criteria for their efficient use and how the warehouse can benefit from AGVs in comparison with normal forklifts. The criteria determination will be based on warehouse operations, design and understanding material flow.

The outcome of the first and second research questions will serve a foundation for the analysis needed to answer research objective 3. Once the criteria and materials flows are determined, the factors influencing the number of AGVs needed are to be understood as well as how they will be applied for the case company. The third research objective will thereby be based on literature findings from the three sections and provide the number of AGVs required at the case company warehouse.

3. Methodology

The sections below explains the research strategy and research design of this study was conducted. The research design was transformed into steps to fit the research objective, with each step being described in detail, including methods of collecting and analyzing data. The section also includes how the quality of the research was validated.

3.1 Research Strategy

Before defining the research strategy, it is important to be aware of the research purpose of the study. The purpose can be initially identified in the way the research questions are asked. According to Saunders, Lewis and Thornhill (2016), there are three categories of research purposes: exploratory, explanatory and descriptive. An exploratory research is used when there is an interest in understanding a phenomenon or a problem. An explanatory study is conducted where there is a causal relationship to be explained. Finally, a study is descriptive when it's purpose is to describe a phenomenon such as an event or a problem (Saunders et al. 2016). According to Höst et al. (2002), the purpose of a study can also be problem-solving. It is also not uncommon that master thesis projects have a purpose of problem-solving. The purpose of this thesis can be categorized into both exploratory and problem solving. It is exploratory as the objective of the thesis is to explore the relationship between usage of AGVs and warehouse layout and material flow. It is also problem solving because the objective is to seek a solution towards an efficient usage of AGVs in the warehouse.

The research strategy then needs to match the purpose. Research strategies can be classified as either case study, survey, simulation or mathematical modeling (Malhotra and Grover's, 1998). A case study has been defined as an empirical study that investigates a modern phenomenon deeply and in its real-life context (Yin, 2014). It was also defined by Eisenhart (1989) as a research strategy that focuses on understanding dynamics present in single cases. The use of case study as a research strategy is most suitable for "how" or "why" research questions, according to Yin (2014). It is also suitable when there is limited control over behavioral events and their impact on the studied phenomenon (Yin, 2014). This study focuses on investigating a modern subject which is usage of AGVs in a specific context that is the production plant of parts and spare parts for the automotive industry. It is then concluded that the appropriate research strategy for this study is case study.

3.2 Research Design

A research design process is developed with the aim of implementing the research strategy, and functions as a plan on how to carry out the research. The research design should be in line with, and based on, the purpose of the research and the research questions (Robson, 2002). Robson (2002) differentiates between a fixed and a flexible design strategy. A fixed design is predetermined prior to conducting the main part of data collection and should not, as the name imply, be changed during the course of the research. A flexible design can and should on the other hand be developed during the research project (Robson, 2002). Case studies typically take on a flexible research design, as the research questions and purpose can be changed over time (Voss et al., 2002). The research design for this study consists of the five areas shown in figure 3.1. The steps are carried out in chronological order with overlapping between some of the steps to achieve flexibility in the research. Each step is explained and described in more detail in the next coming sections in this chapter.

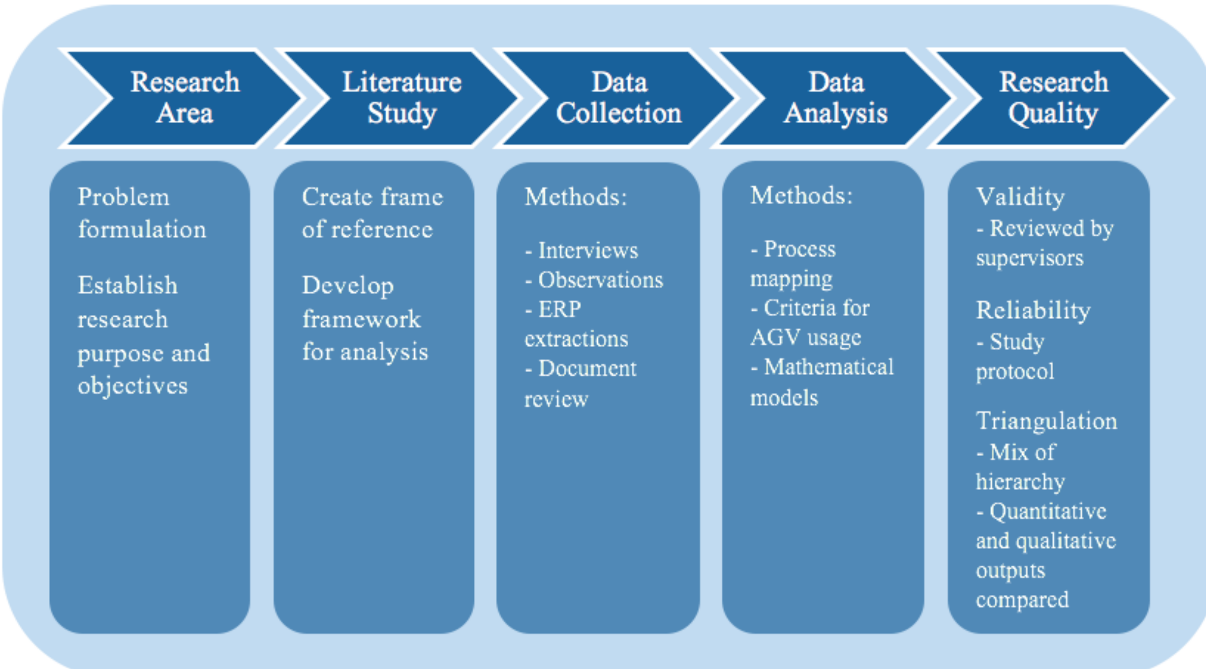


Figure 3.1 Visualization of the research design areas.

3.2.1 Research Area

It was important to first identify and establish the research problem at the beginning of this study. The identified problem was discussed both with supervisors at Haldex and at LTH in order to meet both Haldex' expectations and to reach the required academic level. The identified problem was then broken down into a research purpose, and a set of research objectives. The three developed objectives will help structure the report and will give indications of what data is going to be needed and in which topics literature should be reviewed.

3.2.2 Case Description

Haldex in Landskrona currently produces one main product which is the air disc brake (figure 3.2). Ninety percent of air disc brake demand comes from Haldex' three biggest customers. The plant used to produce brake adjusters, however, that product has recently been moved to another plant. The main focus of Landskrona plant at the moment are air disc brakes and its many components. Some of these components are not only used in the assembly of the finished disc brake but they are also packaged and shipped to customers as spare parts. This study will focus on the warehousing processes and flows concerned with air disc brakes and its three main components: calipers, carriers and brakes pads. The reason is that they have the highest value and physical volume compared to the rest of components handled in the warehouse. According to the logistics manager, they take about 80 percent of the total occupied space in the warehouse (Pålsson, 2018). Therefore, the item categories of finished air disc brakes, calipers, carriers and brake pads are the most relevant to include in the analysis.

Figure 3.2 Main product manufactured at the Landskrona plant, air disc brake (Haldex.com).

3.2.3 Literature Study

The aim of the literature study was to create a deeper understanding of the topics and to identify areas which would help answer the research objectives. The literature was reviewed by reading articles, books and online sources from relevant databases and libraries. The literature was connected to the research objectives and developed into a framework for analysis.

3.2.4 Data Collection

The selection of data collection methods is based on the type on information which is sought after (Robson, 2002). Collected data can be categorized as either qualitative or quantitative. Qualitative data refers to soft data expressed in words or explanations and is suitable for unstructured information such as strategies, thoughts or general intangible information. Quantitative data on the other hand is often more structured and refers to collection and analysis of numerical data (Saunders et al., 2007). The nature of the collected data can also be defined as primary and secondary data. Primary data is new data which is gathered specifically for the research, while secondary data is data which already exists and has been collected for other purposes (Saunders et al., 2007). The research objectives follows a logical order and the order of collecting data should be adapted. The output of the first research objective should result in inputs for the second objective and outputs for the seconds objective to inputs to the third. Data collection for the three objectives were carried out in a chronological order.

Interviews were carried out in order to understand what the current situation in the warehouse look like, as well as how the warehouse will change in the future as a source of primary data. The first interviews were mostly unstructured, which can be viewed as a conversation regarding a specific topic (Robson, 2002). The unstructured interviews were made with the logistics, intern logistics and plant managers in the middle to end of January 2018 (see Appendix A for interview guide). To further understand warehouse operations and future changes, semi-structured interviews were held with managers for production and assembly processes, as well as shift leaders and production engineers in the beginning to middle of march 2018. Interviews were as well used for gathering information regarding AGV usage to be able to answer the second and third research objective (see Appendix B for interview guide). The semi-structured interviews used, as suggested by literature, predetermined questions but the wording and order of asking the questions were changeable. Using a funnel principle, the questions started out on a broader base and as the interview progressed, the questions became more specific and ended with detailed questions (Voss et al., 2002). The questions were modified according to the the interviewee's area of knowledge and the aim of the interview, but the interview guide from Appendix B was used to keep the same structure during the interviews. However, no new interview guide was developed, as the interviews were more open in nature than previous interviews. During interviews, the work was divided between the two authors with one asking questions and the other was responsible for taking notes. This position changed so that both persons held interviews in which they asked questions. Conducted interviews can be found in table 3.1.

Table 3.1 Conducted interviews at Haldex.

Name	**Function**	**Date & time**	**Purpose and Information**
Anders Pålsson	Logistics Manager	18-01-2018 09.00-09.30	Initial problem investigation and background information
Enes Hasic	Internal Logistics Manager	19-01-2018 10.30-11.00	Initial problem investigation and background information
Laurent Berthelot	Plant Manager	07-02-2018 15.00-16.00	Background information and insight on a different plant
Anders Pålsson, Enes Hasic, Philip Andersson and Lars-Johan Andersson	Logistics Manager, Internal Logistics Manager, Production Manager Machining Operations, and Maintenance and Project Manager	01-03-2018 12.30-13.00	Problem discussion and data collection
Anne Andersson	Shift leader	07-03-2018 11.00-11.45	AGV background information
Lars-Johan Andersson	Maintenance and Project Manager	08-03-2018 11.00-11.30	Problem discussion
Philip Andersson	Production Manager Machining Operations	09-03-2018 13.00-13.30	Production rates and throughput information
Ville Husgafvel	Production engineer	16-03-2018 13.30-14.30	Automation project and material flow design

Another method of collecting primary data was do carry out observations. Participant observations can be divided into four categories: complete participant, complete observer, observer as participant and participant as observer. The first two roles requires that the observer's identity is hidden, while in the latter two is is known. In this research, the role which the researchers will have are observers as participant. This role is chosen as the observations will be observing actions, rather than the researchers taking part in the activities (Saunders et al., 2007). The main part of observations were carried out between February and March 2018. The observations were carried out to identify how operations in the warehouse are connected and to visualize material flows, in order to help answering both the first and second research objective. Observations were also made to time transportations and to get handling time for picking and putaway done by manual forklifts. The identification of the handling time was measured by observing and timing the forklifts in different areas in the warehouse both for picking and putaway operations, ending with an average of the observed times. Other than for the flows, observations was used to understand layout characteristics, especially for determining the number of pallet positions in the warehouse. While some pallet positions were possible to identify by using other data collection methods, pallet positions for the different floor storage areas in the warehouse were based upon observations.

Secondary data was collected by ERP extraction in order to understand the material flows and warehouse operations in more detail. The extractions were done during the month of March, and the early beginning of the month of April 2018. Information was gathered regarding product and pallet dimensions to understand how much the manual forklifts and the AGV would be able to load and how the dimensions affected layout characteristics. Understanding current and future demand pattern, and throughput rates of the different manufacturing processes was a key point to be able to answer all of the research objectives. This information was gathered from the ERP with the help of the internal logistics manager and parts of the planning department. Planned orders and forecast for the year 2018 was looked at to evaluate the demand. The throughput rates and takt times for the manufacturing processes were also evaluated by looking at both internal and external planned orders, and how often material were moved between the different areas in the warehouse. To increase the research quality, secondary data for this information was also gathered by reviewing excel documents provided by the logistics manager, the internal logistics manager, and the production manager over emails and as a follow up to interviews. Document review was also done in order to determine travel distances, and was done by measuring a map provided by a production engineer and translating the distance to actual meters in the warehouse. The technical specifications for both manual forklifts and AGVs were reviewed as well to be able to answer the second and third research objective, and were provided by the internal logistics manager and the shift leader for logistics. The document review was carried out during the month of March 2018 alongside ERP extraction and the other data collection methods.

3.2.5 Data Analysis

As data in its raw form does not speak for itself, analysis is necessary to make sense of data and present conclusions (Robson, 2002). The data collection and analysis partly overlapped with each other as to create flexibility in the study. The overlapping meant that additional information which was lacking for the analysis could be gathered to complement the available information and improve the quality of the analysis. The first step in analyzing data is to use the framework for analysis developed in the previous chapter as a guideline to organize data and results. Following the structure of framework illustrated in three parts, each part for each research objective. Data analysis and data collection results are incorporated together. Data collected from interviews to understand how AGVs functioned at Haldex was directly summarized and analyzed after holding the interviews to not forget important details. The same approach was done for analyzing data collected by observations, thus also analyzed and summarized directly after the observation taking place.

Visualizing the flows and warehouse operations was determined to be key in answering the first research questions. Data collected was organized in two categories; either belonging to current situation or future situation. The collected data was then mapped to make it easier to compare both the current and future situation. The outcome were identified changes in material flows that will be used for the second research objective, to determine flows for AGV usage. Based on this outcome, Haldex' previous experience with AGVs, and literature, a set of criteria for efficient AGV usage was determined. The criteria was used as the foundation for comparing the different flows in the warehouse and used to finally select the best flows. Several ways to evaluate the chosen criteria were discussed among the authors. It was decided that a qualitative analysis was more suitable than implementing a weighted grading system. The reason for this decision is the basis of appointing weight for each criteria was not found as well as not necessary to support recommendations. Lastly, to answer the third research objective, concepts and corresponding formulas were adapted from mathematical models found in previous literature studies. These formulas refer to parameters used to calculate the number of AGVs. Models identified in literature were modified to fit the scope of the research and keeping the limitations of the report.

3.2.6 Research Quality

Credibility is an important element to take into consideration when conducting a research study, without it the research findings will not be trusted or considered. Research literature has developed a set of methods that helps mitigate the lack of quality and credibility of a given study. Three aspects, as presented by Yin (2014), should be considered: triangulation, reliability and validity. The way these aspects are both viewed in literature and considered for this study are summarized in table 3.2.

Triangulation is a method used to look at the phenomenon studied from different perspectives, thereby limiting the biases that come from evaluating it from one perspective (Yin, 2014). One way of triangulation is to collect the same piece of information from several sources and/or using different data collection methods (Voss et al., 2002). Another approach to overcome biases in data or constructs built from data is to have a mix of qualitative and qualitative data. The use of qualitative data such as interviews and observations can be useful in determining causal relationships. However, it is often subject to researchers' interpretation and view of the external world. In that sense, qualitative data is often not seen as objective and can yield different results from a researcher to another, even if the research goals and information sources are the same. Therefore, it is important to complement with quantitative data as well, especially if the research is meant to be generalizable. For this purpose, it is important to use triangulation, which is collecting data from multiple data sources, both qualitative and quantitative (Voss et al., 2002). This will also be another way to assure that triangulation of data is achieved.

Validity, in case research, is categorized in three sub-criteria: construct, external and internal validity. Construct validity is the degree to which designed tests or measurements correctly evaluate the concept of interest. As seen in table 3.2, to ensure construct validity, facts should be verified using multiple sources in the data collection phase. This tactic can be achieved in this study by making sure to analyze the same constructs through interviews, observations and data from the ERP system. Another tactic, is to have company interviewees and the supervisor at LTH review the case study draft. Internal validity is verifying and proving that the causal relationships presented are valid. This type of validity is of concern in data analysis, when building relationships between constructs. External validity is whether the built up logic and findings can be replicated beyond the case study at hand or in other words, generalizable (Voss et al., 2002). The findings of this study will be based on a single case study as mentioned in the research strategy. It implies that the logic cannot be immediately replicated to multiple cases, which can constitute some uncertainty as to whether the findings are generalizable. Generalizability is seen as one of the weaknesses of single case study.

Reliability is "*the extent to which a study's operations can be repeated, with the same results*" (Stuart et al., 2002, p.211). Reliability can be achieved by maintaining a database where raw data are stored and can be accessed by other researchers (Stuart et al., 2002). In this study, it is attempted to achieve reliability by maintaining a thorough research protocol which can be made accessible to company representatives.

Table 3.2 . Validity and Reliability tactics in case study taken from Voss et al. 2002 (adapted from Yin, 1994, p.33).

Criteria	**Case study tactic**	**Concerned phase of research design**	**Tactics used in this study**
Construct validity	Use multiple sources of evidence Establish chain of evidence Have informants review draft case study report	Data collection Data collection Composition	The draft report is to be reviewed by case company and academic supervisor Email communication with case company to validate collected information
Internal validity	Do pattern matching or explanation building or time-series analysis	Data analysis	Relationships between constructs explained in data analysis
External validity	Use replication logic in multiple case studies	Research design	Not applicable for single case study
Reliability	Use study protocol Develop case study database	Data collection Data collection	A study protocol in an excel sheet developed and updates throughout the process
Triangulation	Use of multiple sources of data Mix of qualitative and quantitative data	Data collection Data collection	Mix of respondents hierarchy, interviews with operators and managers Extraction from ERP and excel sheets provided quantitative data, checked against interviews output

4. Current Situation at Haldex

This chapter will present the warehouse operations and design aspects of the current situation, as of early 2018, at Haldex' warehouse. It will serve as a basis for later comparison with the future situation in order to answer the first research objective.

4.1 Product Categories

The plant at Landskrona currently produces one finished product which is the Air Disc Brake (ADB). Many components are purchased and processed and then used to assemble ADBs. They are mainly used for that purpose, however, some of them are also directly sold to customers. In this thesis, it was chosen to focus on finished brakes as the only product shipped to customer as it constitutes the majority of outbound shipments. Three main component groups were also chosen as the focus for the analysis. These are called brake pads, calipers and carriers.

To produce one ADB, two brake pads, one carrier, and one caliper are required. The disc brakes are differentiated as left ADB and right ADB, with components mirroring this as well. The rest of raw materials used for the assembly of the disc brake are small in physical dimensions as well as in value, and is therefore not included in this study. Figure 4.1 below shows the process through which each component or raw material goes through, before being assembled into a final air disc brake. All four are referred to as product groups as they comprise several item numbers, which differ in terms of customers, brands and the like.

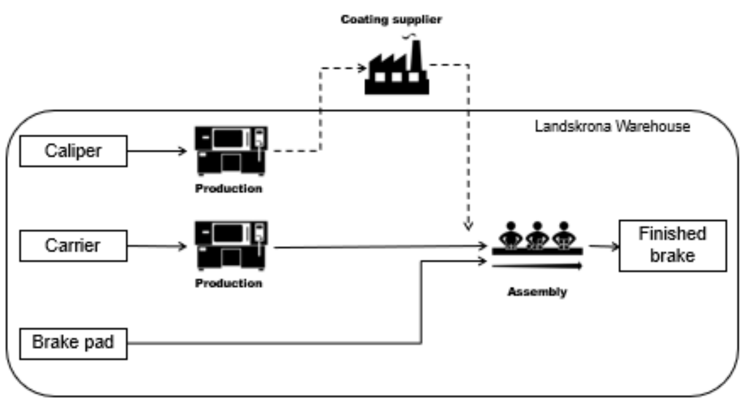
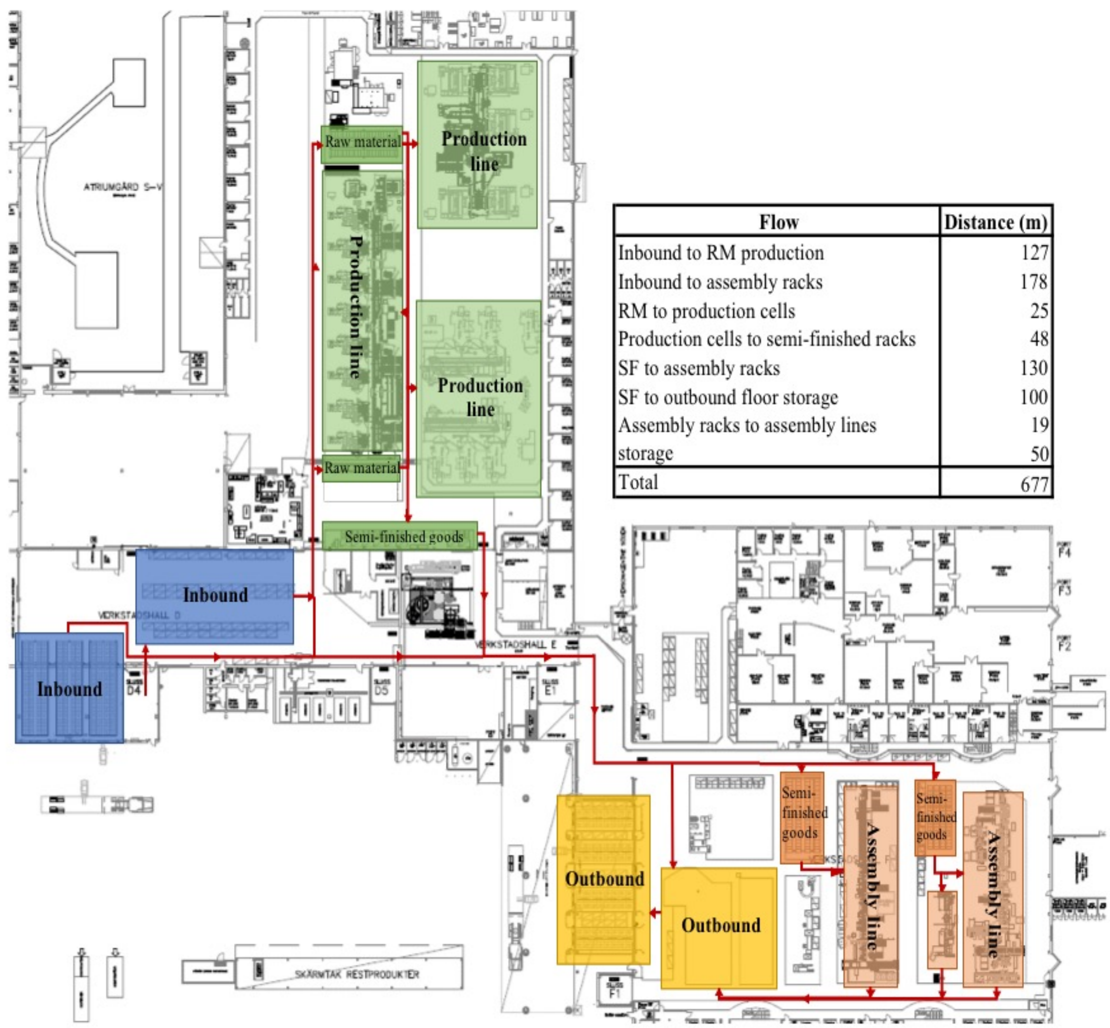


Figure 4.1 Manufacturing process from component to finished disc brake.

The three products categories, calipers, carriers and brake pads, are being processed in three different ways and therefore the material flow varies for each category (figure 4.1). Brake pads are purchased and directly used for assembly, without going through production. Carriers are processed in the production machines, then used in assembly. Finally, Calipers are not only processed by machine but they also require to be coated as a separate process (figure 4.1).

4.2 Current Operations at Haldex

Haldex' warehouse at Landskrona is currently composed of four areas: inbound, production, assembly and outbound (Figure 4.2). The material flow is also shown in the figure and represented by the red arrows linking the different areas. Since this is a production warehouse, a differentiation is made between warehouse processes and manufacturing processes. Warehousing processes are explained using a process flowchart which can be found in Appendix C. There are two different manufacturing processes; production and assembly. The first one transforms raw materials, for calipers and carriers in this case, into semi-finished products. The second one, assembly, is the process where semi-finished products are assembled to make the finished product, air disc brake. Between all these areas, flows of transportation are carried out to move the pallets containing the products. As can be seen in figure 4.2, the total for all transport flows can be summed up to 677 m. The transportation distance of moving goods outside the warehouse, for unloading and loading of goods are neglected as they are out of scope.



Flow	Distance (m)
Inbound to RM production	127
Inbound to assembly racks	178
RM to production cells	25
Production cells to semi-finished racks	48
SF to assembly racks	130
SF to outbound floor storage	100
Assembly racks to assembly lines	19
storage	50
Total	677

Figure 4.2 Layout of the warehouse including distances between areas.

There are two warehouse processes in the inbound area: goods incoming process and putaway process. Upon receipt of a load, document and paperwork are checked, pallets are unloaded from a truck and put outside the inbound dock. The pallets are labelled, and if it applies, go through quality control. In the putaway process, pallets are scanned and stored either in flow-through racks or single-deep racks.

The production area consists of both warehouse processes and a manufacturing process. The warehouse processes are picking and putaway of raw material and semi-finished goods to and from the production cells. The raw material is placed in the flow-through racks north of the production cells, while semi-finished goods are placed in the single-deep racks south of the production cells awaiting transportation to the assembly area. The manufactured process converts raw material into semi-finished goods, ready to be assembled. Three production cells are available for the manufacturing process and can handle different products (Figure 4.3).

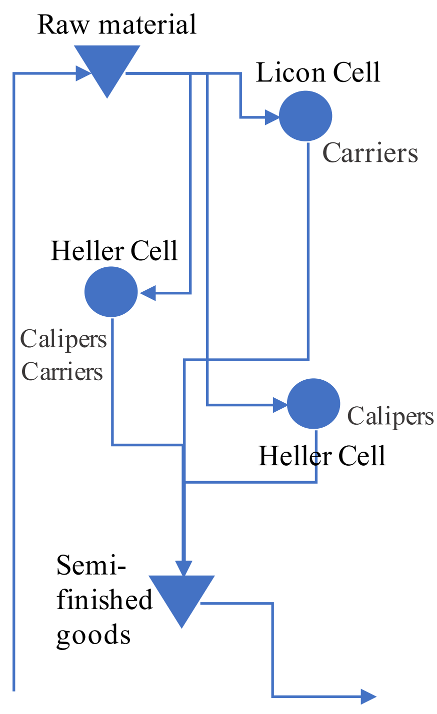


Figure 4.3 Plan flow of production area.

The production cell to the left in the map, Heller cell, mainly produces calipers, but parts of the cell is dedicated to production of carriers as well. The top right cell, Licon, produces only carriers while the lower right cell, Heller, produces only calipers. In total, there are 10 machines dedicated for caliper production and 5 machines dedicated for carrier production. As shown in Table 4.1, the throughput per pallet per hour is 2.6 pallets and 2.4 pallets for calipers and carriers respectively.

Table 4.1 Throughput rate (TH) of production cells.

Component processed	Number of machines	TH (pallets/week)	TH (pallets/shift)	TH (pallets /hour)
Caliper	10	329	20.6	2.6
Carrier	5	269	19.5	2.4
Total	15	598	40.0	5.0

The coating process, which only concerns one component: calipers, is currently outsourced to a subcontractor. The processed calipers in production are then moved to the outbound area and shipped, occasionally being stored in the semi-finished goods area before. The supplier lead time is between 3-4 days, according to the planning department. The stock on hand for those components range between 6000 to 9000 unpainted calipers.

Two warehouse processes, putaway and picking, and one manufacturing process is also the case for the assembly area. Semi-finished goods are transported from the single-deep racks or floor storage in the production area to one of the flow-through racks, depending on which type of product it is. The other warehouse process is to feed the assembly lines. The lines assemble the products into finished goods and are then transported from the assembly lines to the outbound area. There are three assembly lines, Uranus, Tellus and Neptunus. The total throughout for all these assembly lines is summed up to 6.7 pallets per hour (Table 4.2).

Table 4.2 Throughput rate of assembly lines.

Assembly Line	TH (pallets/shift)	TH (pallets/hour)
Uranus	25.4	3.2
Tellus	20.0	2.5
Neptunus	8.3	1.0
Total	53.7	6.7

One of the two warehouse processes in the outbound area is putaway of finished goods from the assembly lines to floor storage. The other warehouse process in outbound area is the loading and shipping of finished goods to customers. When doing so, goods are moved from the indoor floor storage into one of four gates in the outbound area and stored on the floor awaiting the trucks, and then loaded onto the trucks.

4.2.1 Handling Unit and Storage System

The handling unit for the investigated products are pallets, more specifically V-EMB pallets from the L-serie (figure 4.4). The pallets are made up of stackable frames, making the height of the pallet adjustable. Each frame has the outer dimensions of 1225x820 mm with a height that can be calculated as 160mm+195mm x Y (Y= number of frames) (Volvogroup.com, 2018). Typically at Haldex, the three main products, which are being considered for this study, are stored in pallets with either three or four frames. Besides the V-EMB pallet, standardized EU-pallets as well as a type of steel frame are also used due to customer and supplier requirements.

Figure 4.4 V-EMB pallet (Volvogroup.com, 2018).

The storage system at Haldex' warehouse is for the most part work in process stored between different manufacturing processes. Flow-through racks have been put in place in three areas, mainly to facilitate AGV use and movement at the time when it was operating. The rest of inventory is placed on traditional single-deep racks as well as on the floor, occasionally stacked in two levels. It was found important to identify the details and space capacity for each area, as described further.

In the inbound area, there is a storage area with two types of racks: flow-through and single-deep racks. The flow-through racks are placed at the inbound gate and directly connected to the outside yard where trucks are unloaded. The racks consist of twelve lanes, with three levels, resulting in 432 pallet positions (Table 4.3). Each of the lanes is dedicated to an item number. The dedicated policy allows pallets to be stored from the back of the racks and picked from the front. With this use, mixing item numbers in a single lane is not feasible. The single-deep rack storage are divided into six lanes, with varying levels, corresponding to a total of 818 pallet positions (Table 4.3). The single deep rack storage has a shared allocation policy for the group of products dedicated to that area, which is spare parts and slow moving goods. Besides these two storage equipment, a single level flow-through rack has recently been placed. Its purpose is to assist AGVs in moving pallets stored in conventional single-deep racks, and additional pallet positions needed to be moved fast out of the inbound area. As the neither of the single-deep racks or the conveyor have a mechanism to interact with AGVs, manual forklifts are used to pick pallets from regular racks and place them in the single level flow-through rack. An AGV can pick it directly from the flow-through rack.

Table 4.3 Number of pallet positions in inbound area

	Flow-through racks	**Single deep racks**
Number of pallet positions	432	818

The production area can be described as composed of three groups of machine cells, one large group of cells and two smaller ones. Both storage types described earlier are used for work in process in this area. One lane of flow-through rack with three levels is placed south of the larger production cell with 27 pallet positions (Table 4.4). Three lanes, also with three levels, of flow-through racks are placed north of the larger production cell, corresponding to 81 pallet positions (Table 4.4). The flow-through racks are dedicated for raw materials coming from inbound. The flow-through racks in the production area has switched position between north and south of the production cell a number of time during the last 5 years. After being processed, semi-finished goods are stored in single deep racks are placed along the south wall of the production. This storage accounts for 88 shared pallet positions (Table 4.4). When these positions are full, pallets are stored on the floor. Floor storage can typically accommodate approximately 44 pallet positions, stacked in two levels. The semi-finished goods are stored awaiting to be transported to either outbound or assembly.

Table 4.4 Number of pallet positions in production area

	Flow-through racks	**Single deep racks**	**Floor storage**
Number of pallet positions	108	88	44

The assembly hall is composed of three assembly lines with two groups of flow-through racks. One group of racks is dedicated to one component: caliper. The second rack is dedicated to the two other main components: carrier and brake pad. The racks for calipers has 72 pallet positions, with four lanes and two levels (Table 4.5). The racks for carriers and brake pads, also with four lanes and two levels is placed between the assembly lines and corresponds to 56 pallet positions (Table 4.5). The racks are assigned a dedicated storage policy. Multiple single deep racks in the hall (Table 4.5), are dedicated to spare parts and other small products, and are outside the scope of the study.

Table 4.5 Number of pallet positions in assembly area.

	Flow-through racks	Single deep racks
Number of pallet positions	128	Not used for main products

The outbound area is solely floor storage, and range between 150-200 amount of pallet positions (Table 4.6), with on average nine lanes with ten pallets in length. The available floor storage depends on the type of customer, as different customers request different kinds of pallet types. Some pallets can be stacked in two levels, while some cannot, resulting in the range. Before being loaded onto trucks to be shipped to customers, the pallets are stored inside gates connected to the loading area. While there are four gate doors, there is no separation, with for example walls, inside the gates. Inside one gate, there is room to store either two or three lanes with 6 pallets in length. If three lanes of pallets are stored in gate number one, then only two lanes can be stored in gate two. The reason for this is due to the outside forklift will not be able to pick the goods for loading if the pallets are placed to close together. As such, the available pallet positions for all four gates are calculated as every other gate with two lanes and every other with three lanes, both with 6 pallets in length. With the same premises as for the floor storage in outbound area, with pallets sometimes being stacked in two levels, this results in a range of 60-100 pallet positions for all the four gates (Table 4.6).

Table 4.6 Number of pallet positions in outbound area.

	Floor storage	Gate storage
Number of pallet positions	150-200	60-100

4.2.2 Material Handling

All material handling in the warehouse is performed by forklifts considering that the only unit of handling for the investigated products are pallets However, different types of forklifts are needed with respect to the area where they are operated in as well as criteria such as weight and distance travelled. Specifications of the forklifts are shown in Table 4.7, for the purpose of clarifying material handling capacity at the warehouse and to later on have a benchmark when evaluating AGV forklifts.

Table 4.7 Technical specifications and types of forklifts.

	Type of forklift		
	Stacker Truck		Reach Truck
	CAT NSV 16N /16NI D3700	CAT NSV 16N DF2900	Linde R14 1120
Number of forklifts in the warehouse	13	1	4
Max. lift height (m)	3,7	2,9	5,76
Weight Cap. (kg)	1600	1600	1400
Max. travel speed (km/h)	9	9	14
Operating time (travel speed in warehouse + picking and putaway)	1,11 m/s + 1 min	1,1 m/s + 1 min	1,94 m/s + 1 min

A number of different types of forklifts are operating at the plant; namely 14 stacker trucks and 4 reach trucks (Table 4.7). Stacker trucks are smaller in size and are therefore used for narrow aisles and spaces. Reach trucks are used outside the warehouse gates and between the main areas. The main part of the stacker trucks have a maximum lifting height of 3,7 m. The last stacker truck has a lifting capacity of 2,9 m, and is therefore assigned to areas in which there are no high racks.

The stacker forklifts are calculated with a travel speed of 4 km/h (1,11 m/s), because it is the recommended top speed to use in warehouse areas which are also visited by pedestrians. The operating time results in the travel time for the different distances plus picking and putaway time. Observations carried out in the warehouse showed the picking and putaway is on average 30 seconds per process, summing up to one minute in total. As the reach trucks travels with a faster speed of 7 km/h (1,94 m/s), the operating times are shorter. However, the picking and putaway times are kept the same. Neither of the trucks are considered driving top speed, as the distances in the warehouse are relatively short, making the acceleration time too short to hit top speed and safety regulations must be considered.

The pallet weight for the different products range between 281-1109 kg, depending on the type of product inside each product category, as they differ to different customers. Inside each product category, there is not a very large weight difference, and the average per product category is considered representable (Table 4.8). Each product category is different, and as the dimension of the actual products differs, depending on product and for which customer it is intended for, the total units per pallet differs. If using the average pallet weight, then the forklifts can handle maximum two pallets at the time. However, only brake pads and some of the carrier castings have this limit, as those items are the ones with a total pallet weight of <800 kg for the stacker trucks and the AGVs and <700 kg for the reach truck. Haldex' limit of how many pallets can be transported at the time is not only determined by the weight, but also by the number of frames on the V-EMB pallets. If a pallet has three frames, two pallets can be transported at the same time inside the warehouse, and three outside in the inbound area. If a pallet has four to five frames, only one pallet can be transported at the same time inside the warehouse, and two outdoors the inbound/outbound areas. As the affected products range between mainly three to four frames, an average of transportations with one and two pallets are used as the base for calculating the transportation times for the forklifts.

Table 4.8 Pallet dimensions and weight.

Product category	Pallet dimension (mm)	Units per pallet	Average pallet weight (kg)
Brake Pad	820 x 530	402-516	858
Caliper	820 x 930	32	530
Caliper Casting	820 x 730	32	621
Carrier	820 x 930	26-48	342
Carrier Casting	820 x 730	28-100	802
Finished Brakes	820 x 930	12-20	533

As the reach trucks can travel faster, those are mainly used for transportation of goods for the longer distances in the warehouse. However, the reach trucks are the only trucks which can lift high enough to replenish the single deep racks in inbound area, and are therefore assigned to that area as well when needed. Besides the reach trucks, twelve of the stacker trucks are also assigned to the shifts covered by logistics, which mainly operates in inbound area. The forklifts are assigned different tasks as explained by Table 4.9.

Table 4.9 Shifts assignments, tasks and forklifts assigned to the areas at the plant.

Area	**Shift assignment**	**Tasks**	**Number of forklifts assigned per shift**
Logistics (Inbound, outbound and internal flows)	Outdoor	Loading and unloading of goods, scanning and labeling pallets	2
	Inbound	Put away of goods inside the inbound area, for all kinds of racks	2
	Replenishment	Replenishment of goods for all areas in the warehouse	1
	Recycling	Picking and recycling of recycling material in the all warehouse areas	1
	Extra	Assigned to either of the above areas if and when necessary	Varies
Productio n	N/A	Feed production cells and move semi-finished goods from cells to racks	4
Assembly	N/A	Feed assembly lines and move finished goods to outbound area	2

Besides the forklifts assigned to logistics, there are also four forklifts assigned to the production area and two forklifts assigned to the assembly area. The forklifts in the production area cover the different production cells, one for each cell. The operators for these forklifts are responsible for feeding the machine new material from the flow-through racks, and to pick and putaway semi-finished goods from the cells to the semi-finished goods racks and floor storage. In the assembly area, the two forklift operators have similar tasks as in production, where they feed the assembly lines, as well as move finished goods into the outbound area. They also do replenishment of the supermarket area if necessary and if there is time available.

4.3 Map of Current Situation

A process map, inspired by Value Stream Mapping, was made to summarize data and to provide a clearer picture of the warehouse operations for the current situation. Presented in figure 4.5, activities such as transportation, production, assembly are visualized.

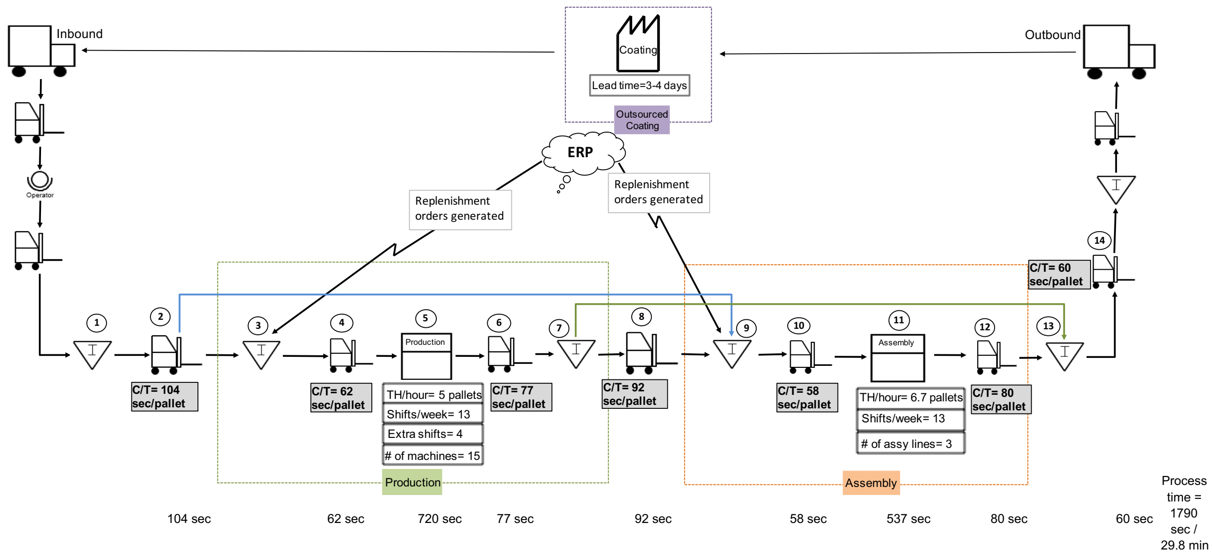


Figure 4.5 Process map of the current situation.

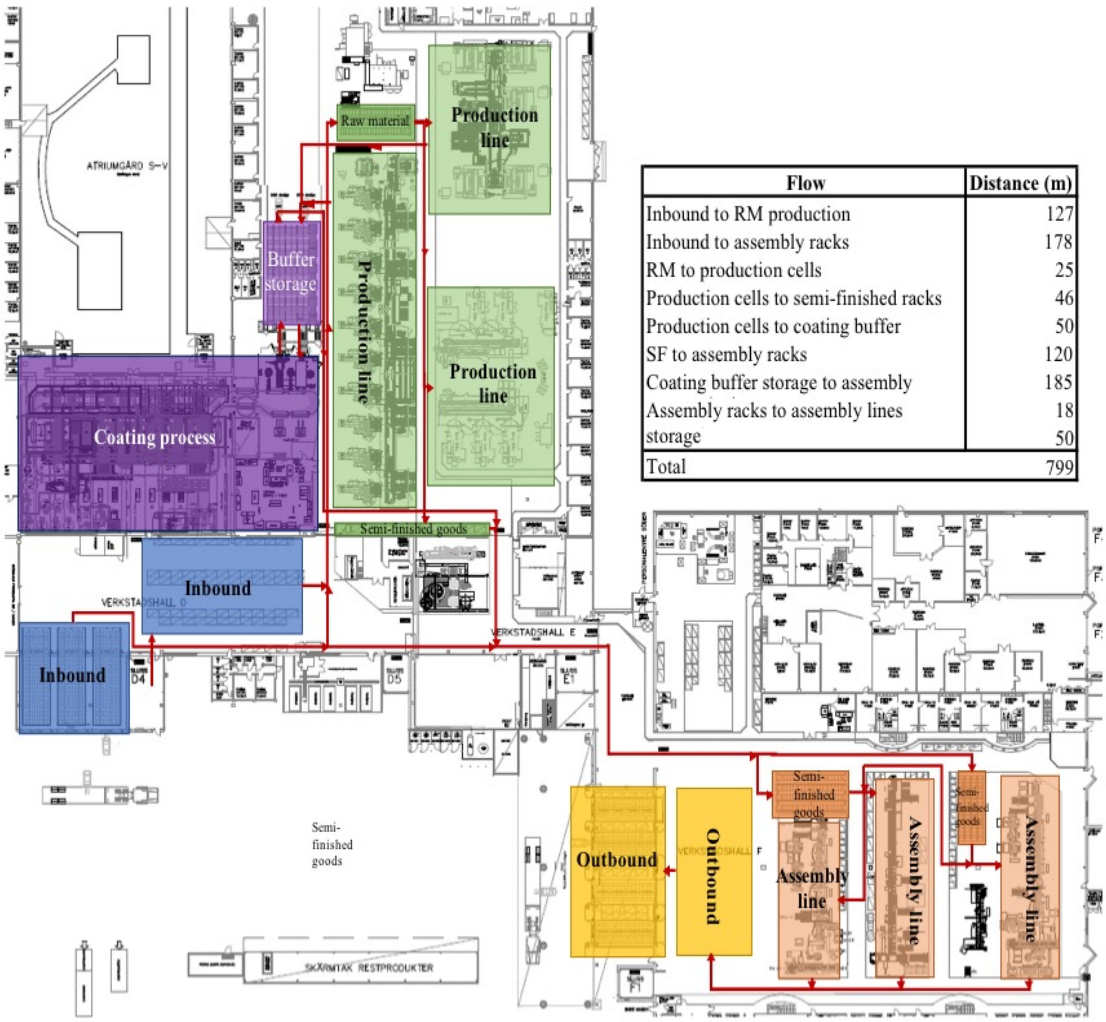
Process time for production and assembly is calculated to 720 seconds per pallet and 537 seconds per pallet, respectively. The total process time, of transportation and manufacturing processes, is currently 29.8 minutes per pallet. However, this does not include any waiting time at any of the processes. While brake pads and carriers only have the lead time of when they are placed in storage, the lead time for calipers highly affect the total lead time for finished brakes. The total lead time for finished brakes is much longer than necessary, with calipers having a lead time for the coating process for 3-4 days. What should be noted for both the lead time and the process time is that not all of the products go through each of the processes. After goods are stored in their dedicated placed in the inbound area, different products are transported to different locations. The brake pads are directly transported to the assembly area indicated in figure 4.5 by a blue arrow. Calipers and carriers are both transported to the production area and go through the manufacturing process. Calipers are then transported to the outbound area, being shipped out for coating at a supplier, indicated in the purple box in the top of the figure. Thus, the calculation for the transportation time for activity 8 is an average of transporting goods from the production area to either the racks in the assembly area or to the floor storage in the outbound area. When the calipers return from supplier, they are shipped directly to the assembly area where also are moved after the manufacturing process. The total transportation time for all transportation is 8.88 minutes per pallet. Due to the long lead time for shipping out calipers for coating, the overall lead have plenty of potential to be shorten. Mapping the warehouse operation not only helped clarify how materials flow through areas of the warehouse, it has also shown to be useful in identifying a number of issues or potential improvement areas in material handling.

5. Future Situation

This chapter includes future changes in the warehouse operations and design. The aspects are then analyzed in comparison with previous chapter, the current situation, in order to establish how the changes affected the material flows. The results of the changes should answer the first research objective.

5.1 Future Changes in processes

The future changes to the Landskrona plant will mainly be about the coating process of calipers that will be done inhouse starting 2019. There will also be an upgrade of the production and assembly capacity with the objective of keeping up with the demand growth in the coming years. The new expected layout is presented in Figure 5.1. However, all processes will be kept at their designated areas. All transportations flows in the warehouse (as shown in figure 5.1) can be summed up to a total of 799 m in terms of distance inside the warehouse. Additional distances of transportation to unload and load incoming and outgoing trucks are not included, as the place where the trucks can park vary depending on the schedules and congestions in the inbound and outbound area.



Flow	Distance (m)
Inbound to RM production	127
Inbound to assembly racks	178
RM to production cells	25
Production cells to semi-finished racks	46
Production cells to coating buffer	50
SF to assembly racks	120
Coating buffer storage to assembly	185
Assembly racks to assembly lines	18
storage	50
Total	799

Figure 5.1 Future changes to the material flow and added coating process starting 2019, including transport distances.

The throughput rate will increase to 5.6 pallets per hour for both calipers and carriers, with the two new machines in the production process (table 5.1). The new machines are dedicated to producing carriers and will extend the left production cell in the warehouse, reducing empty space in front of the semi-finished goods storage. The new production cell with the two new machines are expected to be up and running by the middle of 2018.

Table 5.1. Expected throughput rate of the future production process.

Component processed	Number of machines	TH(pallets /week)	TH(pallets /shift)	TH(pallets /hour)
Caliper	10	329	20.6	2.6
Carrier	7	311	24.5	3.1
Total	17	640	24.5	5.6

Haldex has decided to invest in its own coating process at the Landskrona plant which will impact the operations and material flow in the warehouse. The coating process is expected to start in the beginning of 2019. The new coating process will be placed in relation to the production area, as well as in proximity to the inbound area (Figure 5.1). Currently, only calipers are planned to go through the coating process. To not affect the production flow, a buffer storage area with flow-through racks will be placed in relation to the coating and production processes as to integrate them. Raw material for the coating process coming directly from the receiving area will be stored in the racks, as well as finished calipers. Manufactured calipers will be taken from the production cells and placed in the racks directly connected with the coating process. Within the coating process, a pallet with the manufactured calipers will be taken from the buffer storage rack and placed on a conveyor connected to the coating by a robot. The calipers in the pallet will then be placed on hangers and moved into the coating area where the hangers are dipped in ED paint, cooled down and return back into the loading and unloading area. The takt time per hanger is expected to be 6 min, and the total throughput rate for the coating process is expected to be 10 pallets per hour. The unloading of calipers from the hanger to a pallet is done by a robot. After a pallet is full, a new barcode will be printed with the same pallet ID, but including the information that the containing calipers have been painted and are ready for assembly. After the coating is finalized, the calipers will be placed back in racks, awaiting pickup for transportation to the assembly process.

As calipers in the future will be coated in-house, there is no longer a need for a flow going from the production area directly to the outbound area. Therefore, the calipers will be moved from the buffer storage racks directly to the flow-through racks in the assembly area. The carriers will continue to be moved either directly from the production cells if there are forklifts available or from the semi-finished goods rack to the designated flow-through racks in the assembly area. The racks for carriers will continue to be shared with the brake pads, being transported directly from inbound to the racks in assembly. As of year 2019, a new assembly line will be introduced and implemented at the plant, while the smallest assembly line is moved to Mexico. The changes in the assembly area results in a new capacity. The expected throughput is increased to a total of 7.2 pallets per hour (Table 5.2). With this new assembly line, the flow-through racks dedicated to calipers will be slightly moved and changed direction in order to ease the handling for feeding the assembly lines (see figure 5.1). The movement from assembly lines to outbound area, and from outbound area to loading of goods, will continue to be the same as the current situation in the warehouse.

Table 5.2 Expected throughput rate for future assembly process.

Assembly Line	TH (pallets/shift)	TH (pallets/hour)
Uranus	25.4	3.2
Tellus	20.0	2.5
New Line	12.0	2.0
Total	57.4	7.2

A rearrangement of the storage allocations for the flow-through racks in the inbound area will be the result of the new coating process. More raw material will be dedicated to the flow-through racks in the inbound area, and products with lower volume will be moved into the storage racks in the inbound area. In relation to the new coating process, a buffer storage consisting of flow-through racks will be placed in the production area. The buffer storage will consist of seven lanes with three levels each. Five of those lanes will be dedicated for inbound to the coating process, 210 pallet positions, except one level which will be only for empty pallets, 15 pallet positions. The other two lanes will be dedicated for outbound from the coating process, 90 pallet positions, awaiting pick up to be moved to either finished material racks in the production area or directly to the assembly area. All pallet positions in the buffer storage except for the empty pallet lane is dedicated to calipers, as that product is currently the only product which is planned to go through the coating process.

The new assembly line will result in a decrease of floor storage space in the outbound area. An approximation shows that the available space will be about five lanes with 10 pallets in length. This corresponds to about 50-100 pallets positions, depending on type of pallet and if it can be stacked in two levels.

5.2 Demand Growth

There has been a noticeable increase in demand for disc brakes (figure 5.2), and Haldex had to adapt production rates to keep up with the demand increase. With the coating process brought in house by the beginning of 2019, a smoother material flow and planning is essential. In 2019 Haldex expects to sell 10 269 finished brakes per week and in 2020, 10 115 finished brakes weekly. The slight decrease in demand by 2020 compared to 2019 is due to movement of parts of the production and assembly to North America, as they will support their own sales.

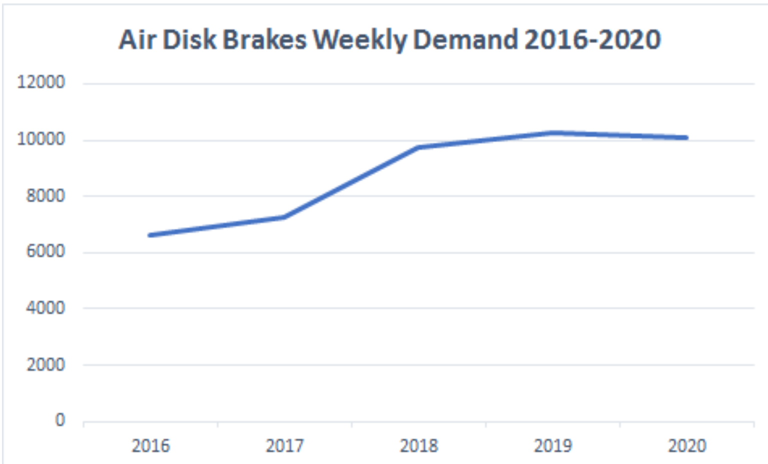


Figure 5.2 Predicted demand growth over the 2020 horizon

Demand and production planning at Haldex are updated on a weekly basis. The graph in figure 5.3 shows the weekly demand distribution for finished products during 2018. It can be said that the demand per week resembles a uniform distribution. The average demand over year 2018 is 9441 finished brakes per week, typically ranging between 8000 and 11 000 per week. There are few exceptions during summer and winter holidays where there is a slight decrease as well as some increases (figure 5.3). These variations are counteracted by adjusting the production capacity and the inventory on hand.

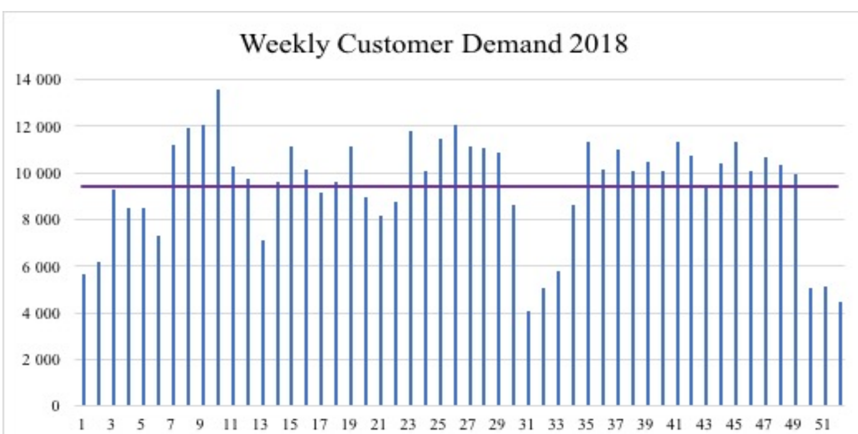


Figure 5.3 Demand distribution for finished brakes per week over the year 2018

Inventory days is one of the most important key performance indicator (KPI) for Haldex and inventory is continuously adjusted according to the demand. The company's goal is to have a safety stock equivalent to a week for raw materials and semi-finished components, and three to four days for the finished brakes. When the demand changes from week to week, the material flow is affected. It is therefore important that the material handling capacity is able to accommodate the added volume. The future changes described in the previous section of this chapter suggests a changes in processes and an upgrade in capacity following the increase in customer demand.

5.3 Map of Future Situation

A process map, again inspired by VSM, was also made for the future situation in order the be able to compare and analyze the data (Figure 5.4). The data for the expected throughput and capacity of the new machines for the production process, coating process and the new assembly line. The new process times are 643 seconds per pallet, 360 seconds per pallet and 500 seconds per pallet for the processes respectively. The new total process time for finished brakes is 35.1 minute per pallet, or weekly demand resulting in 260 hours for all processes and travel. Due to layout changes, the distances and as such the transportation time will also change in the future. The transportation time and capacity information is also based on estimations by observations and information provided by Haldex personnel and can therefore be considered variable. Total future transportation time is calculated to be 10.1 minutes per pallet. With the new added coating process, the total lead time is reduced for calipers as the 3-4 days for coating at a subcontractor is no longer required. Thus, the lead time for finished brakes is reduced as well. The new coating process also means that calipers no longer are shipped out to a supplier for coating, reducing the average number of deliveries per day. However, due to the increase in demand, it is expected to ship about 13 shipments of finished brakes per day on average.

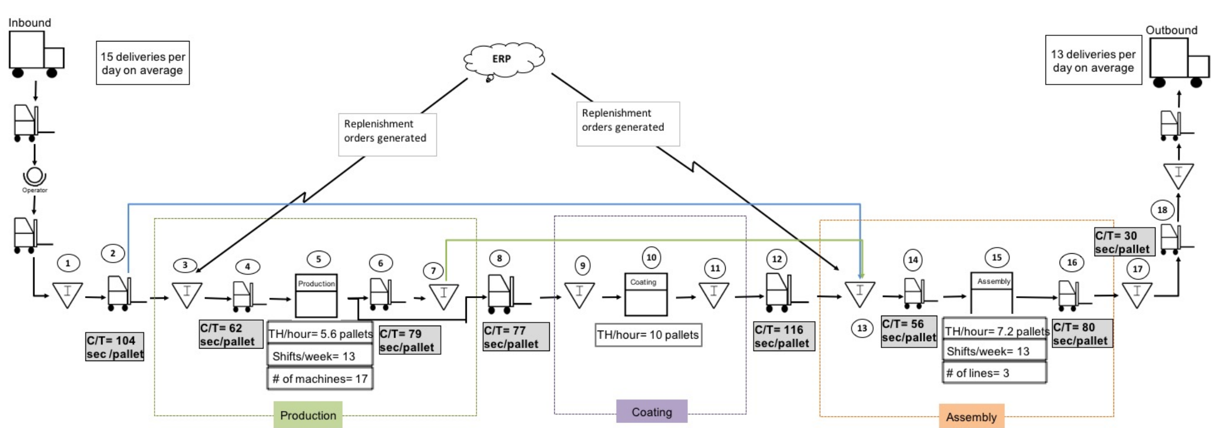


Figure 5.4 Process map of the expected future situation.

5.4 Analysis of Future Warehouse Changes

Haldex’ investment in its own coating process at the Landskrona plant will naturally solve some issues in the material flow. The material flows of shipping uncoated calipers to the subcontractor and receiving back coated calipers will both be eliminated. Accordingly, the flow from inbound to assembly of coated calipers and that of uncoated calipers from production to outbound will also be removed. The new coating process also changes storage allocation in the flow-through racks in the inbound area, as coated calipers will no longer be shipped to the warehouse and require storage space. As a result, more of the other high volume products can be stored in the flow-through racks instead, leading to a decrease in handling and movement as the double handling of moving from single deep racks to flow-through single level rack is no longer necessary.

The total lead time for calipers will decrease significantly when implementing the coating process. The current lead time for the coating process is 3-4 days per pallet, while the inhouse process will take 10 min per pallet. However, the total transportation time for forklift operations will increase compared to the current situation in the warehouse. With all transportation flows added, the difference in total transportation time will be 1.18 minutes per pallet longer with the new coating area. The increase of transportation time is due to the increase in transportation distances, with 122 m for all flows, as well as a higher number of flows. While the total transportation time is longer, calipers are no longer required to be transported from the production area to outbound or all additional handling with transporting coated calipers from inbound into the assembly area. The new buffer storage dedicated for the coating process, and the placement of this, leads to two additional transportations flows: from the production cells to storage and from storage to assembly area. In addition to the new buffer area, the flow-through racks have been moved multiple times in the production area during the last 5 years. Distances, travel time and operation time for the current situation are all calculated with the racks being placed north of the production cells. The flow-through racks used to be placed south of the production cells, thus distance both from inbound and to assembly was shorter. The movement of the racks was to be able to fit the new machines in the production area, as well as avoiding congestion by the semi-finished goods storage. The idea of less congestion seems unlikely in the production area with the added flows from the coating buffer storage. More forklifts will have to share the same space, especially in the area south of the production cells around the semi-finished goods storage.

The new added production cells and assembly line increases the capacity and throughput rates of those processes to keep up with the expected increase of the demand. However, no new storage space besides the buffer storage will be introduced in the warehouse at either of those processes, keeping the number of storage positions the same. This means that the time that goods are stored in the current storage spaces will decrease, and more frequent movement to replenish those will be required.

The floor storage space in outbound will decrease with the new assembly lines arriving in 2019, thus leading to more goods having to be stored inside the gates as well as a more frequent flow of outgoing shipments. Currently, the storage space inside the gates are limited, as goods can only be stored on one side in the gates to make room for forklifts and handling. This results in unutilized space due to the the current layout and placement of the gate doors. The most critical changes happening in the warehouse are summarized the table 5.3 below for clarification purposes.

Table 5.3 Summary of changes in the warehouse and the impacts.

Area	Change	Impact
Inbound	Storage allocation	Less semi-finished goods requiring storage in flow-through racks leaving available locations for raw material.
Coating	Added process	Decrease in lead time for calipers. Added internal material flows More available storage for semi-finished calipers.
Production	Added production cell	Higher throughput rates. More frequent replenishment due to not adding storage locations for raw material/semi-finished goods.
Assembly	Added assembly lines	
Outbound	Decreased floor storage	Less storage locations available for finished products before shipping.
Entire warehouse	Added material flows	Longer transportation time Higher congestion risk.

6. AGV Flows

This chapter aims to present findings and analysis for the second research objective, for which flows AGVs should be used. Previous usage of AGVs are presented first, including how Haldex used the vehicles at the time they were operating and issues they faced during that time. The analysis of flows is then presented, including the criteria of which the selection of flows is based upon.

6.1 Previous Usage of AGVs at Haldex

In 2013, Haldex integrated two forklift AGVs into their warehouse operations and they have been running until late 2017. The AGVs are from Toyota Material Handling, of the model SAE160 BT Autopilot Stacker. This model allows for manual as well as fully automated operations. The AGVs used Toyota Material Handling's guidance control system without any integration with the Landskrona plant's ERP system. To navigate in the warehouse, the AGVs use laser reflectors and the internal WLAN connection. The laser reflectors were as well used for identifying obstacles on the path.

The vehicles were operating between inbound, production, assembly and outbound area, as shown in figure 6.1 below. The transportation tasks were manually triggered by operators or shift leaders. Pickup and replenishment request for pallets being stored in flow-through racks were requested manually by pushing a button at the rack. If pallets were stored in a single-deep rack, the operators had to first align pallets constituting a lane on a dedicated floor space or place on a conveyor and then requests the AGV. The vehicle picked up all pallets in that lane, if not told otherwise. An AGV would pick up pallets from inbound and transport them to flow-through racks either in production or assembly area, depending on the type of product. They would also pick up finished goods from assembly area and place them in outbound floor storage awaiting shipping to customers.

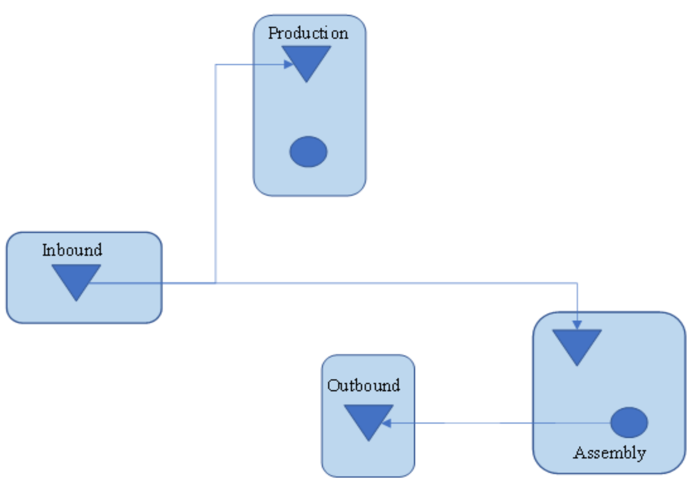


Figure 6.1 Previous AGV flows up until late 2017.

As for obstacle avoidance, the AGVs would stop and wait for the obstacle to be removed, done manually by an operator. The top travel speed of the AGVs in automated mode was 6 km/h (Table 6.1). Pallets could be picked up and delivered to and from racks, conveyor belts and floor spaces, no other handling unit besides pallets were handled by the AGVs. The AGVs were only able to do pickup and putaway on a maximum height of two levels in the racks, with a maximum lift height of 2.35 m (Table 6.1). When picking from the racks, the AGVs used scanners to identify correct pallet location, which were programmed into the GCS. The only type of rack which the AGVs could pick from were flow-through racks, the single-deep racks were not programmed into the AGVs' system. When picking from conveyors or floor spaces, the AGV had to use scanners to evaluate where the pallet was located. This resulted in the AGV having to drive up to the location slowly and taking longer to pick up the pallet than from a rack. To not affect the efficiency of the AGVs, Haldex invested in spare batteries which were charging while the AGVs were operating. The batteries would be manually replaced during shifts. The time it took to replace batteries was negligible according to the shift leader.

Table 6.1. AGV specifications.

AGV Specifications	
Number of AGVs in warehouse	2
Operating hours/truck/day	24
Max. lift height (m)	2.35
Weight Cap. (kg)	1600
Max. travel speed (km/h)	6
Operating time (travel speed in warehouse + picking and putaway)	1.67 m/s + 40 sec

The implementation of the AGVs was considered successful according to the shift leader, in terms of saving resources. It was estimated that two manual operators were saved with AGVs, which could instead be used in the production processes. However, before benefits could be seen, some challenges were met during the implementation phase. The original designed routes for the AGVs lead to some issues and several trial and errors were made before finding the best solution. Unsuitable traffic rules was one important problem encountered. In the beginning, the AGVs could travel in both sides in a aisle. This was found problematic, as operators would sometimes park their forklifts in the aisles, creating obstacles for the AGV and therefore increased waiting time. In addition, the operators would sometimes put pallets in the aisles as well, creating more permanent obstacles. The obstacles affected the overall productivity and traveling time of the AGVs. To solve this, the traffic rules were changed to allow AGVs to only travel on one side of the aisles. The personnel was trained on how to adapt to the new traffic rules, to avoid any mishaps. A second issue encountered concerned the poor WLAN connection experienced at first. The connection interruptions caused long and frequent stoppages as AGVs rely on a well-functioning WLAN connection to operate smoothly. It took approximately 1.5 to 2 years to achieve smooth and continuous operations.

It is known that Haldex experienced issues and problems during the time the AGVs were operating in the warehouse. For the sake of analyzing where AGVs should be used in the future and how many are needed, the most critical issues are summarized in table 6.2 below.

Table 6.2 Identified issues with current AGVs.

Area	Issue
Traffic rules	1. Traffic rules are important in order to avoid congestion between AGVs and manual forklifts, since both use the same routes.
Network	2. Reliable network and/or backup solution is required to avoid stoppage due to interrupted connection.
Capacity	3. Current two AGVs can only pick from two levels, while all flow-through racks have three levels.
Picking and putaway	4. Picking and putaway of material is not possible for single-deep racks in the warehouse. Using AGVs for picking and putaway of material in floor storage takes longer than in flow-through racks.
ERP	5. Current two AGVs were not linked to ERP system, tracking pallet movements in real time was not possible.

6.2 Criteria and Flow Selection

To be able to establish which flows could be improved with AGVs, a set of criteria is developed based on literature, issues that Haldex experienced during their previous AGV usage, and the future situation in the warehouse. Both literature and Haldex identify the importance of dealing with congestions to ensure efficient usage. Congestions can occur both in terms of having to change routes, or stop, in order to avoid obstacles, or sharing routes with other AGVs and normal forklifts. Haldex was dealing with congestions by assigning the AGVs to one side in the aisle or paths, so that forklifts or pedestrians which needed to stop could do so on the other side. What should be remembered for future usage is that if the number of AGVs are increasing and sharing paths, the risk of congestions will increase with the risk of collision with other AGVs as well as the obstacles. The distance also affect the congestion problem, as the longer the distance is, the higher change of intersections and pedestrians on the route. Besides congestion, travel time is an important part of the distance to consider. Long distance transportation tends to be faster with AGVs than with normal forklifts, as the AGVs can operate at 2 km/h higher speed compared to normal forklifts. Long distance transportation also means longer non-value adding time allocated to operators. It is more useful to automate long-distance transportation to either reduce labor costs or to reallocate the operators to the manufacturing processes. Long distances in the warehouse at Haldex should be 100 meters or longer, considering the different flows in the warehouse from the expected future situation.

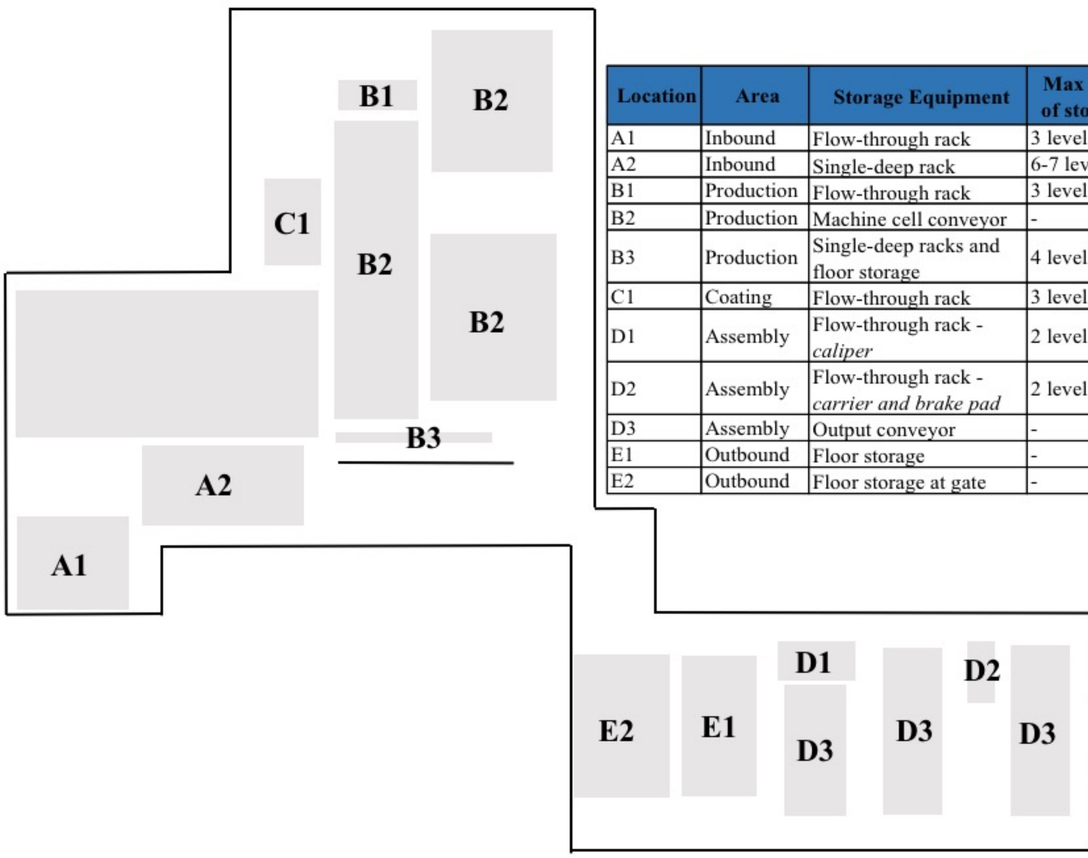
Also affecting time to perform a task is the type of storage equipment at the pickup and putaway locations. The AGVs are limited to flow-through racks, floor storage and conveyors, and cannot perform picking or putaway of material from single-deep racks. Handling time for picking and putaway at the flow-through racks for AGVs was estimated to be 20 seconds per pallet per task, while for the normal forklifts they were observed at 30 seconds per pallet per task. However, the estimation for picking or putaway of material at floor storage could not be done for AGVs, as they are currently not operating. Information collected through interviews suggests that AGVs have to slow down and use the sensors in order to identify the exact placement of the pallet on the floor. From that, the conclusion drawn is that handling time significantly increases for floor storage. Summarizing the discussion, the flows for AGV transportation should meet the following criterias presented in table 6.3.

Table 6.3. Set of criteria for determining AGV flows.

Criteria	Priority	Purpose
Type of storage equipment	First	Increased efficiency if flow-through racks are used, while floor storage affects handling time. Single-deep racks are not AGV-compatible.
Distance	Second	AGV operates at a higher speed and can therefore save traveltime
Congestion risk	Third	High congestion risks can result in obstacle avoidance and unnecessary stoppings, thus increasing the travel time

As the type of storage equipment highly affect the efficiency of AGV usage, in terms of handling time and the AGV can even be used, this criteria has been selected to have the highest impact on the selection of the flows. Second priority is the distance of the flow, meaning that the longer the flow is, the better suitable it is for AGV usage. This is because the AGV can travel faster than normal forklifts, thus saving transport time. The congestion risk, while literature and Haldex stating its importance, is determined to have the third lowest impact to the selection of flows. This is because most of the flows have a relatively high congestion risk, and as the warehouse is crowded and narrow in general, the risk of congestion will be quite high no matter of which flow is being considered.

All flows must be considered for a thorough analysis, as material and goods are being transported between all areas in the warehouse. For the sake of clarifying the flows, the pickup and delivery locations in the warehouse are shown and denoted as stated in figure 6.2. The flows between the locations will as a result be called for example A1-C1, meaning the flow between inbound flow-through racks and raw material storage in the production area. The evaluated flows will be based on the flows for the future situation in the warehouse, as flows the current situation in the warehouse are changing and therefore neglectable.



Location	Area	Storage Equipment	Max level of storage
A1	Inbound	Flow-through rack	3 levels
A2	Inbound	Single-deep rack	6-7 levels
B1	Production	Flow-through rack	3 levels
B2	Production	Machine cell conveyor	-
B3	Production	Single-deep racks and floor storage	4 levels
C1	Coating	Flow-through rack	3 levels
D1	Assembly	Flow-through rack - *caliper*	2 levels
D2	Assembly	Flow-through rack - *carrier and brake pad*	2 levels
D3	Assembly	Output conveyor	-
E1	Outbound	Floor storage	-
E2	Outbound	Floor storage at gate	-

Figure 6.2 Picking and putaway locations in the warehouse.

Figure 6.2 shows that many of the picking and putaway locations are not compatible with AGV usage, due to the type of storage equipment. Each area in the warehouse is assigned a letter, locations in inbound are called A, production are called B, coating are called C, assembly are called D and outbound are called E. Out of the locations that are the most compatible, location A1, B1, C1, D1 and D2, only D1 and D2 can be utilized to full capacity by the AGVs due to the vehicles not being able to lift higher than two levels in the racks. The other suitable locations all have three levels. It is possible for the AGVs to pick up material from the production cell and assembly lines, but not to leave material. However, it has been observed that both B2 and D3 have a high risk of congestion, with the operators and normal forklifts moving back and forth between the cells/lines and storage. In general, all locations in the production area have relatively high risk of congestion, due to the fact that there are plenty of picking and putaway locations, narrow aisles, and operators sharing the same space. The same issue of congestion applies to the coating and assembly area as there are multiple forklifts and operators in and around the areas possible resulting in obstacles for the AGVs.

Changes in the layout also affects the distances, and additional flows leads to an increase in total transportation distance, thus more time, to produce a finished brake. With literature identifying transportation time as not adding value to the finished product and highly impacting the total cost, this criteria is of great importance. Based on the above presented criteria, all flows in the warehouse are evaluated in table 6.4.

Table 6.4 Flow evaluation based on criteria

Flow	Criteria				Suitable for AGVs
	Suitable Storage Equipment	Distance		Congestion risk	
C1-D1	Yes	Long	185 m	High	Yes
A1-D2	Yes	Long	178 m	Medium	Yes
A1-B1	Yes	Long	127 m	High	Yes
D3-E1	Yes	Short	50 m	Medium	Yes
B2-C1	Yes	Short	50 m	High	Yes
B1-B2	Yes	Short	25 m	High	Yes
B3-D2	Partly	Long	120 m	Medium	Yes
B2-B3	Partly	Short	46 m	High	Yes
E1-E2	Partly	Short	20 m	High	No
A2-A1	No	Short	20 m	Low	No
D1-D3	No	Short	18 m	High	No
D2-D3	No	Short	18 m	High	No

In the table, the flows which meets the criteria is presented first, based on the priority of the criteria mentioned previously. As such, the flows having suitable storage equipment is presented, then sorted by distance and then lastly based on the congestion risk. The first six shown flows all have suitable storage equipment of flow-through racks, however only the first three of those also have a long distance over over 100 meters. Out of these three flows, only A1-D2 have medium congestion risk compared to the other flows, therefore scoring the highest of the flows which meets all criteria. However, both C1-D1 and A1-B1 have both suitable equipment and long distance, making them top candidates after A1-D2 for the AGV flows. The flows which are described are partly having suitable storage equipment are B3-D2, B2-B3 and E1-E2. B3 uses both single-deep racks and floor storage, thus the AGV would only be able to pick up or put away material if the goods are stored on the floor. What should be noted though is that due to the long distance, using an AGV for B3-D2 could still be beneficial as the savings in travel time can make up for the increase in handing time. In the outbound area, the E1-E2 flow is possible with AGV, however the short distance and the fact that both locations uses floor storage results in it not being a candidate for the selection of AGV flows. The last three presented flows do not have suitable storage equipment and are therefore not considered.

To better support the selection of top candidates, a comparison of using normal forklifts and AGVs are presented in table 6.5. The transportation time, meaning both the travel time for the distance and the handling time for picking and putaway is presented. Handling time for picking and putaway summed together is 60 seconds for normal forklifts and 40 seconds for the AGVs. In this analysis, it is assumed that the vehicles only carries and handles one pallet per travel. Travel time is calculated with normal forklifts driving at 4 km/h, while the AGVs can drive at 6 km/h.

Table 6.5 Difference in transport time for the selected flows.

	Transport time (travel time + handling time) in seconds		
Flows	**Normal Forklift**	**AGV**	**Difference**
1. A1-D2	220.2	146.8	73.4
2. C1-D1	226.5	151.0	75.5
3. A1-B1	174.3	116.2	58.1
Total	621.0	414.0	207.0

The second flow has the highest difference for using AGVs instead of a normal forklift, with every transport taking 75.5 seconds, or 1.26 minutes. The A1-D2 flow has a slight lower difference than the second, with every transportation taking 73.4 seconds (1.22 minutes). The A1-D2 flow is for moving brake pads from inbound to the assembly area. Because there are two brake pads to every finished brakes, it is believed that the demand for this flow is slightly higher than for the others. The last flow as close to a minute's difference for using an AGV. Overall, all these flows will lead to a decrease in transport time if replaced with AGV, resulting in a total save of 3.45 minutes per pallet for all flows (Table 6.5). It is suggested for Haldex to implement these flows in the presented order. Due to the number of different issues during the last implementation phase, each flow is suggested to be up to standard before implementing a new one. However, the time of 1-2 years is took to implement a flow last time is not realistic, as Haldex is now informed of the potential problems and can mitigate the risks better. As such, the implementation of the flows can somewhat overlap in order to also keep up with the demand. The final selected flows are shown in figure 6.3.

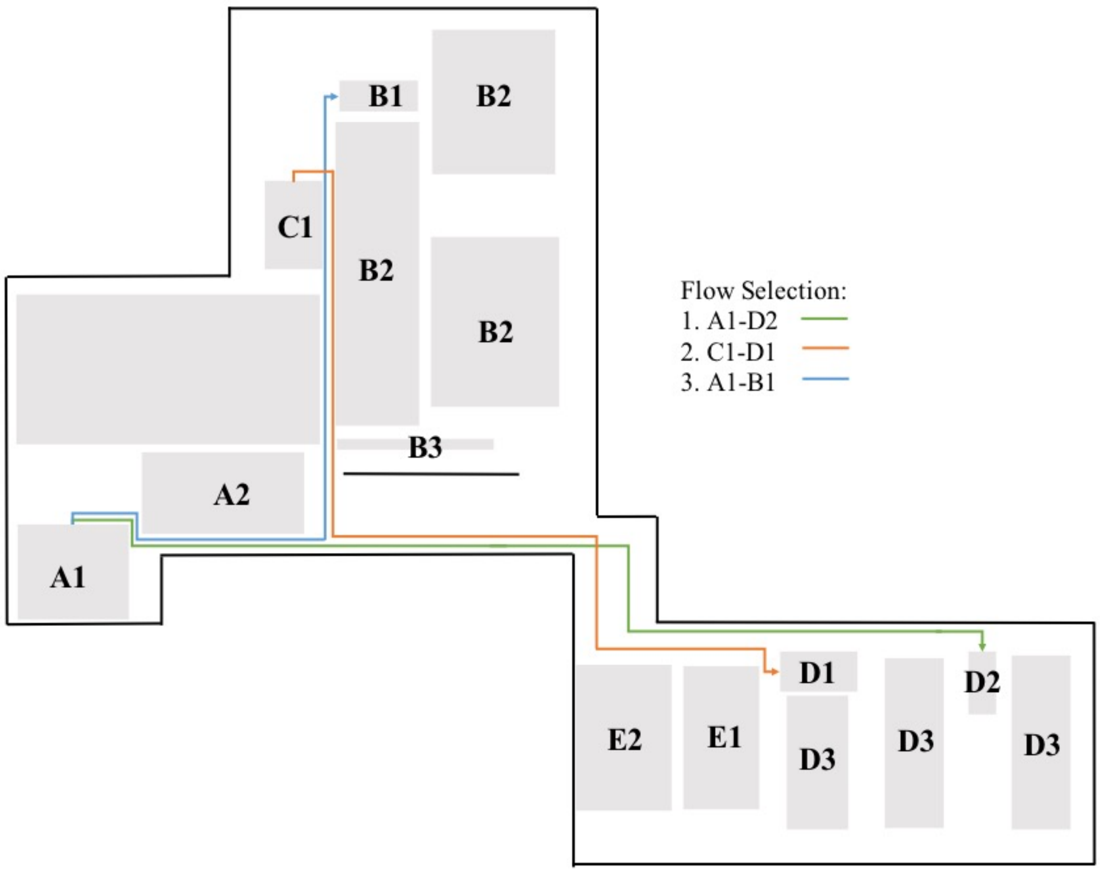


Figure 6.3 Selection of flows and implementation order for scenario 1.

Implementing AGVs for more than these flows are possible, and the selection is then recommended to also be based on the set of criteria, keeping distance and storage equipment type with the most weight. Added AGV flows should as such rather have floor storage than single-deep racks, even if the handling time will slightly increase for floor storage handling compared to flow-through racks. If floor storage flows are used, the savings in travel time for using AGVs compared to normal forklifts should compensate for the increase in handling time. Flows which are using single-deep racks should have the lowest prioritization. With this in mind, the first scenario which is recommended to Haldex is the implement the first three flows as shown in figure 6.3. The second scenario is to implement the additional five flows which are also suitable for AGV usage, which was shown in table 6.4. In the second scenario, the implementation of the additional five should not be carried out prior to having successfully implemented the first three, as they are considered to have the most impact.

7. Number of AGVs Required

In this chapter, the number of AGVs needed for the selected flows is presented and explained through two different scenarios. A sensitivity analysis is performed at the end to assess the robustness of the results. The formulas used to reach those results are adapted from mathematical models found in the literature. Before calculating the number of AGVs required, the parameters influencing the decision need to be introduced in the context of the warehouse at Haldex. The main parameters that affect the fleet size decisions, as discussed by Ujvari and Hilmola (2006), can be classified into three categories: travel distance and routing, delivery request rate and layout flexibility.

7.1 Layout Flexibility, Travel Time and Delivery Request Rate

The layout flexibility of a warehouse highly influences the distance to be travelled by an AGV and the routing it will be subject to (Ujvari and Hilmola, 2006). When a warehouse layout is flexible, it offers many options when it comes to routing and path selection. Finding the shortest route for an AGV can lead to travel distance being minimized. Following interviews and observations made at Haldex, two factors are noticed. The first factor is the mix of traffic, with pedestrians and forklifts using the same routes. The second factor is that the choices of routes to be used by forklifts and vehicles are limited, due to the nature of the production activity. Route optimization will not be considered in this case. Consequently, travel distance calculations were made based on the only routes available, which are the ones currently used by regular forklifts. Some traffic rules are nonetheless possible and necessary to separate AGV and regular forklift traffic. One of them previously used by Haldex is dedicated one side of the travel lane to AGVs. While layout flexibility affects the fleet sizing decision through travel distance and routing, another parameter of the number of AGV decision is delivery request rate.

The replenishment of racks between different areas at Haldex is done according to production and assembly planning needs. Transportation tasks are requested when production or assembly are in need of material. Delivery request rates were then calculated according to the average throughput rate of production and assembly depending on the served flows. The detailed calculations of production throughput rates can be seen in Appendix E and those of assembly in Appendix F. The delivery request rates for the chosen flows are shown in table 7.1 for scenario 1, and in 7.2 for scenario 2. The delivery request rate from inbound location A1 to production location B1 is calculated as the average production throughput rate in addition to a lead time. This additional lead time is estimated as the assignment waiting time and is divided into two parts. The first part is the time it takes for an AGV to pick up the delivery request from A1 and drop it off at B1. The second part is lead time of feeding the machine cells meaning moving pallets from storage racks and placing them inside the cell using a regular forklift. The average assignment waiting time for the flow A1-B1 is estimated to be 10 percent of the hourly production demand.

Table 7.1 Delivery request rates (pallets per hour) between locations - scenario 1.

	B1	**D1**	**D2**	**Pickup rate per location**	**fsi**
A1	4.2	0	1.1	5.26	0.40
C1	0	7.9	0	7.92	0.60
Drop-off rate per location	4.2	7.9	1.1	13.2	-
fdj	0.32	0.60	0.08	-	1

The delivery request rate from location A1 to location D2 is the calculated based on the average assembly rate as well as the proportion of brake pads packed and shipped directly to customers. The assignment waiting time for this flow is assumed to be 10 percent as well. The number of pallets of brake pads needed to satisfy the assembly demand is 1.1 pallets per hour (packing unit is equal to 402 brake pads per pallet). The flow from C1 to D1 transporting calipers from coating to assembly is calculated based on the assembly average throughput of 7.2 pallets of caliper per hour. An lead time of 10 percent is also added to get the delivery request rate of 7.9 pallets every 60 minutes. The delivery rates of the additional flows in scenario 2 are calculated according to the same structure and are presented in table 7.2

Table 7.2 Delivery request rates (pallets per hour) between locations - Scenario 2.

	B2	B1	C1	B3	D1	D2	E1	Pickup rate per location	fsi
A1	0	4.2	0	0	0	1.1	0	5.26	0.15
B1	4.2	0	0	0	0	0	0	4.16	0.12
B2	0	0	2.7	3.4	0	0	0	6.14	0.18
C1	0	0	0	0	7.9	0	0	7.92	0.23
B3	0	0	0	0	0	3.4	0	3.41	0.10
D3	0	0	0	0	0	0	8	7.92	0.23
Drop-off rate per location	4.158	4.158	2.73	3.41	7.92	4.51	8	34.8	-
fdj	0.12	0.12	0.08	0.10	0.23	0.13	0.23	-	1.00

7.2 Calculating the Number of AGVs Required

The number of AGVs required increase with the number of transportation tasks and their arrival rate. Therefore the number of material flows chosen to be covered by AGVs have a positive relationship with the number of vehicles. Two scenarios for this decision will be presented. The recommended flows, presented in the previous chapter, will serve as input for the first scenario, which is the initial implementation of AGVs. The second scenario will include four additional material flows that are recommended be implemented in the future, and the outcome of number of vehicles needed for that scenario. The calculations are presented in scenario 1, and will be similar to steps and formulas used for scenario 2.

The calculations used to determine the number of AGVs required are adapted from the fleet sizing mathematical model by Koo, yang and Suh (2005). This annotations used in the model are as follows:

- n: number of pick-up/drop-off locations
- m: number of vehicles
- ρ: vehicle utilization (= total AGV travel time/total vehicle time available)
- f_{ij}: delivery request rate from location i to location j
- t_{ij}: vehicle travel time from location i to location j
- lu: sum of loading and unloading time
- F: delivery request rate between all location ($F = \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}$)

The first part of the model is to calculate loaded travel time. The mean and variance of loaded time $t_l$are calculated according to the following formula:

$$E(t_l) = \sum_{i=1}^{n} \left[\sum_{j=1}^{n} \{(f_{ij}/F)(t_{ij} + lu)\} \right]$$

$$V(t_l) = \sum_{i=1}^{n} \left[\sum_{j=1}^{n} \{(f_{ij}/F)(t_{ij} + lu)^2\} \right] - E^2(t_l).$$

The second step is calculating the empty travel time, E(t_e) by taking the average of the net flows of all locations. The net flow of a station is obtained by calculating the difference between the request rates picked up at this station and the request rates dropped off at the same station (Maxwell and Muckstadt, 1982). Before that, those rates are each multiplied by the vehicle travel time $t_{ij}$and excluding the loading and unloading times. The net flows of each stations are summed and divided by the F the sum of request rate in order to have the average empty travel time E(t_e). Mean loaded travel time and mean empty travel time are summed to constitute the vehicle travel time E(t_v). The initial number of AGVs can be at this point determined by calculating vehicle utilization. The vehicle utilization ρ can be obtained, according to Koo, Yang and Suh (2005), by dividing the total travel time $T_l$by the total time an AGV is available T_a. The formula is as follows: ρ = $(T_l\ /T_a)^{+}$. The "+" is used to round up to the positive value of the answer. Since a sample of one hour of operations is used. $T_l$is calculated as the product of the average travel time E(t_v) and the total request rates F.

The pick-up/drop-off locations that serve the chosen flows are known and are presented in the previous chapter (section 6.2). Vehicle travel time t_{ij}, loading and unloading times lu are calculated and presented in appendix D and serve as input data for both scenarios.

7.2.1 Scenario 1

This first scenario accounts for the use of AGVs for three flows that can be implemented today: inbound to production (A1 to B1), inbound to assembly (A1 to D2) and coating to assembly (C1 to D1). Delivery request rates f_{ij} between these stations are presented in table 7.2 in the previous section (7.1). The average loaded travel time was calculated and found to be equal E(t_l)= 2.33 minutes per delivery request with the total delivery request rate between all stations equal to

F=13.2. The variance of loaded travel time is V(t_l) =0.07min. The average empty travel time E(t_e) = 2.92 minutes per request. The netflow calculations can be seen in table 7.3. The average vehicle travel time is obtained by summing the average loaded travel time and the average empty travel time, and is equal to E(t_v) = 5.25 minutes per delivery request.

Table 7.3 Empty travel time calculation - scenario 1.

Station	**Unit loads delivered from this station**	**Unit loads delivered to the station**	**Net flow**
A1	7.2	0.0	7.2
C1	14.7	0.0	14.7
D1	0.0	14.7	14.7
D2	0.0	2.0	2.0
Total empty travel time	-	-	38.5
Mean empty travel time per request	-	-	2.9

To find the initial number of AGVs, vehicle utilization is calculated and presented in table 7.4. It is estimated that the AGV is available T_a= 60 minutes. The initial vehicle utilization is found as 115 percent which means that two AGVs are needed. However, it is important to note that this number does not include assignment waiting time which was part of the model presented by Koo, Yang and Suh (2005). The impact of assignment waiting time was however partly mitigated by taking an hourly delivery request rate and including the lead time of the assignment. It is also important to note that the result does not take into account the vehicle waiting time that might be encountered due to congestion in traffic and other technical stoppages. This factor is important to discuss in the case of Haldex warehouse.

Table 7.4 Vehicle utilization and number of AGVs Results - Scenario 1.

Average vehicle travel time (in minutes)	5.25
Vehicle utilization without blocking time	115%
Proportion of blocking time	15%
Vehicle utilization including blocking time	**135%**
Number of AGVs needed	**2**

Although AGV blocking time is not simple to estimate, especially before the number of AGVs is decided; it is a factor that should be taken into account. According to Ujvari and Hilmola (2006), the higher the vehicle number, the higher the AGV blocking time. An excessive number of vehicles can hinder the traffic to run smoothly and therefore cause AGVs to stop and wait for the each other to pass. At Haldex the risk of congestion can be estimated to be quite high because of obstacles that can be encountered. The layout of the plant is characterized by narrow aisles and a few choices of routes that vehicles can take in order to serve the flows. If an AGV is travelling along the flow from inbound to assembly, there is a high risks of congestion along that route. Starting from the pickup location which is the flow through racks in inbound, pedestrians and manual forklifts are found in that area. Examples of activities that involve pedestrians and forklifts are moving pallets from the gate to single-deep racks storages, moving between the gate and the goods incoming office as well as other offices as seen in the map. Regular forklifts especially can also be met anywhere along that route. The risk of traffic stoppage in the three other flows can be considered lower but still present. In production, the concerned route is less used than the other side of the production hall, however replacing machine waste bins is done in that side and can be a barrier in the AGV routes. In assembly, regular forklifts can occasionally travel along the AGV routes. It is therefore reasonable to estimate that AGVs will encounter obstacles which will result in some blocking time. However, as primary data about the use AGVs in the warehouse and the lack of information about the detailed configuration of both traffic control, it was found more reasonable to review literature studies for this estimation. Following a study by Koff (1987), blocking time was estimated to be 15 percent of total travel time. After adding the blocking time, the vehicle utilization becomes 135 percent (Table 7.4). As a result, the number of AGVs required is two vehicles, each with a mean utilization of 76 percent.

7.2.2 Scenario 2

The same logic has been applied to the second scenario, with five additional material flows that are possible to implement in the future, meaning after some minor changes have taken place (see section 6.2). In this scenario, the sum of delivery request rates are F=34.8. The average loaded travel time is found E(t_l) = 1.69 minutes per request, and the variance V(t_l) =1.08 minutes per request. The mean empty travel time E(t_e) = 1.6 minutes (table 7.5). The mean vehicle travel time = 1.93 minutes. This gives a vehicle utilization of 189 percent before vehicle blocking time is accounted for (table 7.6). Vehicle utilization, which includes loaded and empty travel time and blocking time, is 218 percent suggesting a fleet size of either three AGVs. With a decision of three vehicles, the individual vehicle utilization would be 73 percent. While with two vehicles, individual utilization would be 109 percent. The two vehicle decision can cause tasks to be delayed. To avoid the interruption of flows and delay in production and assembly, flows can momentarily be aided by manual forklifts. However, as a full automation of warehouse operations are one of the future goals of the company, the investment in a third AGV is justifiable, especially that the demand is continuously increasing and more capacity investments could be made in the future.

Table 7.5 Empty travel time calculation - Scenario 2.

Station	**Unit loads delivered from this station**	**Unit loads delivered to the station**	**Net flow**
A1	7.2	0.0	7.2
B1	1.0	5.3	4.2
B2	2.2	1.0	1.1
C1	14.6	2.2	12.5
B3	7.0	1.6	5.4
D1	0.0	14.6	14.6
D2	0.0	2.0	2.0
D3	3.9	0.0	3.9
E1	0.0	3.9	3.9
Total empty travel time	-	-	54.9
Mean empty travel time	-	-	**1.6**

As Haldex long term plan of increasing the automation level of logistics activities, the need of fourth AGV is investigated. An additional AGV will be needed if production and assembly capacities are each increased by at least 25 percent. The upgrade in capacity means for example purchasing additional machines and assembly lines. When increasing delivery request rates by 25 percent, total utilization rate is approximately 296 percent, which equals 74 percent utilization for four AGVs.

Table 7.6 Vehicle utilization and number of AGVs Results - Scenario 2.

Average vehicle travel time (in minutes)	3.26
Vehicle utilization without blocking time	189%
Proportion of blocking time	15%
Vehicle utilization including blocking time	**218%**
Number of AGVs needed	**3**

7.2.3 Sensitivity analysis

The result of number of vehicles required depend on a number of variables that could be seen as uncertain. To evaluate the robustness of the output, its relationships with these variables need to be tested. Two variables will be evaluate to determine the extent to which the influence the final result.

The blocking time and vehicle availability are two variables that are predicted based both on literature and the understanding resulting from data collection at Haldex. Vehicle availability is based on the premise that downtime of vehicles will be equal to the time it takes to switch AGV batteries. This operation according to interviews does not take significant time. It is also assumed that the battery switching operation will take place outside the normal shift, either before or after shifts. The sensitivity analysis for the first scenario (table 7.7) and the second scenario (table 7.8) suggest that the output does not change with the increase of vehicle downtime. Downtime inputs from 8 minutes until 32 minutes per shift were evaluated. As seen in table 7.7 and 7.8, a decrease of 2 percent in vehicle availability leads to an increase of utilization rate of only 2 to 3 percent. Therefore, if downtime is 32 minutes the number of AGVs for the first scenario is maintained at 2 AGVs and for the second scenario, 3 AGVs. More than 32 percent can be considered as a major problem rather than routine downtime.

Table 7.7 Sensitivity analysis with respect to availability of AGVs for scenario 1.

Downtime per shift (in minutes)	Vehicle availability Percentage (per shift)	Utilization rate	Number of AGVs needed
0	100%	133%	2
8	98%	135%	2
16	97%	137%	2
24	95%	140%	2
32	93%	142%	2

Table 7.8 Sensitivity analysis with respect to availability of AGVs for scenario 2.

Downtime per shift	% vehicle availability per shift	Utilization rate	Number of AGVs needed
0	100%	218%	3
8	98%	221%	3
16	97%	225%	3
24	95%	229%	3
32	93%	233%	3

AGV blocking time in not only a variable used as input to the number of the AGVs decision, but it is also a variable dependent on the result itself. Therefore its estimation can only be used as an indication rather than a certain value. A sensitivity analysis in this case is valuable in order to find out how it affects the result of the study. Appendix G and H present the result of the sensitivity analysis with respect to vehicle blocking time for scenario 1 and 2, respectively. Blocking time percentage of vehicle travel time is increased within the range of 10 to 30 percentage, found as an indication by literature. For the first scenario, a blocking time percentage of 10 percent yields a vehicle utilization of 127 percent. When blocking time is increased to 30 percent of travel time, vehicle utilization is 150 percent, suggesting that the number of AGVs, for all blocking time values, is 2 AGVs. The same result has been found for the second scenario where the number of AGVs is 3 for all probable values of blocking time.

8. Conclusion

This chapter presents the findings and conclusions to the three research objectives. The final recommendations to the case company, are proposed with respect to each objective. The chapter also includes a section covering suggested future studies on the topic of this research.

8.1 Research Objective 1

The increase in demand have highly impacted warehouse operations at Haldex and will continue to do so as demand is continuously rising. To keep up with this increase, a new production cell with two machines will be added and implemented during the middle of 2018. The new machines will produce carriers, resulting in parts of the other production cells can go back to being dedicated to calipers, also to keep up with demand. The added production cell results in a an overall higher throughout rate of 5.6 pallets per hour, compared to the old throughput rate which was 5.0 pallets per hour. The increase in throughput will result is a higher requirement for replenishment of the machines and storage locations, as no new additional storage locations are planned in this area for either raw material or manufactured carriers. The same issue apply to the assembly area. An additional assembly line will be implemented in the end of 2019 and increase the throughput rate by seven percent. The added assembly line also affects the available storage locations in the outbound area. The new line will partly take up the space which is currently dedicated for floor storage for finished brakes before being shipped out to customers.

The largest change occurring in the warehouse is the addition of the coating process. Being implemented in the beginning of 2019, the process will significantly reduce the lead time for calipers, as they currently have to be shipped to a subcontractor. Thus, the lead time will go from 3-4 days per pallet when shipping the calipers to a subcontractor to the inhouse process having a throughput rate of 10 min per pallet. As semi-finished carriers will no longer have to be shipped out and returned, flows carrying calipers going from production to outbound, and from inbound to assembly will be removed. As a result, storage space will be freed in inbound flow-through racks; affecting the storage allocation of those racks. However, with the new buffer storage which will be implemented directly in relation to the coating area, additional flows from production cells and raw material from inbound are required. The buffer storage will add 210 pallet positions for inbound and 90 pallet positions for outbound to the coating process.

The result of new added processes and changes will be the added frequency of material flows in the warehouse. The increase in flows leads to an increase in transportation time, as the new flows are a total of 122 m longer added together compared to the flows for the current situation. Thus, transportation time will also increase with 3.22 minutes per pallets for all flows together. In extension to increased travel time, the increased number of flows and frequency of those affect the congestion risk in the warehouse. More flows required more traveling, thus more forklifts operating in the same area. There is especially a high risk of congestion in the production and coating area, as the aisles between production cells and coating storage and process will be made more narrow. These issues relate to the second research objective and how the issues can be solved with AGV usage.

8.2 Research Objective 2

After establishing how the changes affected the material flows, the flows that would benefit by AGV usage was then determined. Due to the addition of material flows after changes has been made, using AGV seems likely in order to create efficient flows in the warehouse. All flows were evaluated according to a set of criteria, which were derived from AGV requirements identified in literature and from Haldex' previous experience with AGVs. The criterion which was considered to have the highest impact on the selection was the type of storage equipment at the picking and putaway location. As the AGVs are most efficient with flow-through racks, can be used for floor storage but is not efficient and cannot be used for single-deep racks, the flows were evaluated based on how they met this criterion. The second most important criterion was the distance of the flow, as the AGVs can operate at a higher speed than normal forklifts, total travel time could be significantly decreased when using AGVs. The last criterion, also with the lowest impact was the risk of congestion. With a high risk of congestion possibly resulting in stopping due to obstacles, the flows which had a lower risk were considered better suitable for AGV usage.

The flows were analyzed based on the established criteria, with the distance and type of storage equipment having the most weight for the selection. Two scenarios were determined, with the first scenario being the main one recommended to the case company. In the first scenario, it is recommended to firstly implement the flow between the flow-through rack in the inbound area and the flow-through rack assigned for raw material in the production area. Secondly, the flow between the flow-through racks in the coating area and the flow-through racks dedicated to calipers in the assembly area should be covered. Lastly, the flow moving brake pads between the flow-through rack in inbound and the flow-through rack in assembly should be covered by AGVs.

Using AGVs for the first three flows instead of normal forklifts will save 3.45 minutes per pallet in total. To solve the possible congestion issue by the coating area, as discussed in 8.1, a fourth flow is suggested. It is recommended to add a flow-through rack north of the production cells, going in the reverse direction of the current one. If doing so, unpainted calipers can be moved from production cells to the reverse flow-through racks, be picked up by and AGV and placed in the coating storage. It is recommended to implement these flows in the suggested order, with partial overlapping. If Haldex wishes to implement more flows in the future, the selection of those are suggested to be based on distance and storage equipment type. This means, that flows which have floor storage should be prioritized over flows that have single-deep racks even if the handling time for floor storage will increase. The increase in handling time should be compensated by a reduction of travel time for using AGVs instead of normal forklifts. As such, the recommendations for the second scenario is to implement the eight flows meeting the criteria, as discussed from table 6.4 in chapter 6.

An issue that Haldex experienced previously and will have to consider for the flows is the lifting capacity of the current AGVs. The AGVs can only lift up to two levels in the flow-through racks, while the flow-through racks in inbound, production and coating have or will have three levels. It is therefore suggested to evaluate if replacing the current AGVs with ones that can lift all three levels when the contract for the current ones end. The evaluation of acquiring new AGVs is however not done in this study due to limitations in the scope.

8.3 Research Objective 3

The parameters influencing the number of AGVs required are arrival rate of loads, empty travel, waiting and blocking time. All parameters have a positive relationship with the number of AGVs needed. Each of these parameters depend on a one or more factors. Empty travel depends on how sophisticated the operational control system is and travel distance is influenced by layout flexibility. When a layout is flexible, it offers opportunities to reduce distances and congestion risks through routing optimization. That is not the case for Haldex' warehouse. For the case company's warehouse, the lack of flexibility in the choice of routes affects negatively the travel distances and therefore travel times.

Given the nature of production activity at Haldex, transportation of materials is centered around production and assembly scheduling. Arrival rate of loads, or delivery request rate, was thereby calculated based on the hourly throughput rate of production and assembly in the future situation. The waiting time for each request was estimated based on the travel time and the storage lead time. These two elements together with travel distances and loading and unloading time were used to calculate the loaded travel time. The second output is the empty travel time, obtained by calculating the net flow from and to each station. Both the loaded and empty travel times constitute the total travel time of a vehicle, which can be used to determine an initial number of vehicles. However, an important factor should be regarded and is the vehicle waiting time caused by stoppages called blocking time. This parameter is also regarded as dependent on the number of vehicles chosen.

In line with the suggested flows analysis, two scenarios are presented to calculate the fleet size needed for Haldex. The first scenario takes into account three flows that can be implemented with the predicted future warehouse design. The second scenario provides a solution for the implementation of five additional flows. The results of the first scenario indicate that two AGVs should be initially used. The second scenario outcome generate that a third AGV should be added. The results are based on the assumption that blocking time is 15 percent of the vehicle travel time. The vehicle is estimated is to be available all the time with no downtime included.

To demonstrate the the number of vehicles required is still two AGVs with utilization of almost 80 percent. This recommendation is proposed with the premise that at least one of the AGVs is able to load pallets from the third level. In the future, to be able to cover the suggested eight material flows in the second scenario, a fourth AGV is needed when the production and assembly capacities increase by at least 25 percent.

8.4 Theoretical Contribution and Limitations

During the initiation phase of literature review, there seemed to be a lack of link between changes in warehouse layout and automated handling. Most identified areas of literature covering warehouse layout was focused on designing a warehouse, rather than redesign and the impacts of the changes. After finalizing this thesis, it is believed that parts of the findings can be used as the bridge between automated handling and changes in warehouse layout. Another aspects which was also not identified in theory was a straightforward way to determine how and where AGVs are efficient to use. As such, the criteria which was developed in section 6.2 can be viewed as a guideline for other researchers evaluating similar research objectives.

Due to the limitations of time, areas of analysis had be excluded from the study. A cost analysis of the implementation of additional AGVs has not been made, or replacing the current AGVs with new ones. It has also not been consider if and how using AGVs for the selected flows, or any flows in the warehouse can reduce labor costs, even if literature suggest so. Other aspects which literature determine to be crucial with AGV usage are safety and environmental aspects, due to the limitations of the scope neither of these aspects were considered in detail.

8.5 Future Study

To increase knowledge in the area of automated handling and warehouse operations and design, it is suggested to further look into the different types and models AGVs would impact the warehouse operations. What should also be considered is how to implement the AGVs in order to ensure efficient usage and to avoid issues. Another aspect which can be considered is the connection of change management and AGV implementations and the implications in personnel. To further improve the quality of this topic and determining number of AGVs needed in a warehouse, simulations should be made of the waiting and blocking time.

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Appendix A.
Initial interview with the case company

Practical questions:
Can we write the company name in the report (since the report will be public)?
Any confidential information that we can’t use?

Driverless forklifts:
What kind of Automated forklift is it?
When they were operating, what routes did they have?
What are the main reasons for making this investment?

Problems:
What problems were there before the ERP system was changed?
What KPIs are you using and which are not performing well?
Are all deliveries to customers on time?

Appendix B.
Interview Guide (for AGVs)

Purpose:
Identify the background of AGV implementation in the warehouse, how they operate (previously and currently) and the corresponding benefits and obstacles encountered.

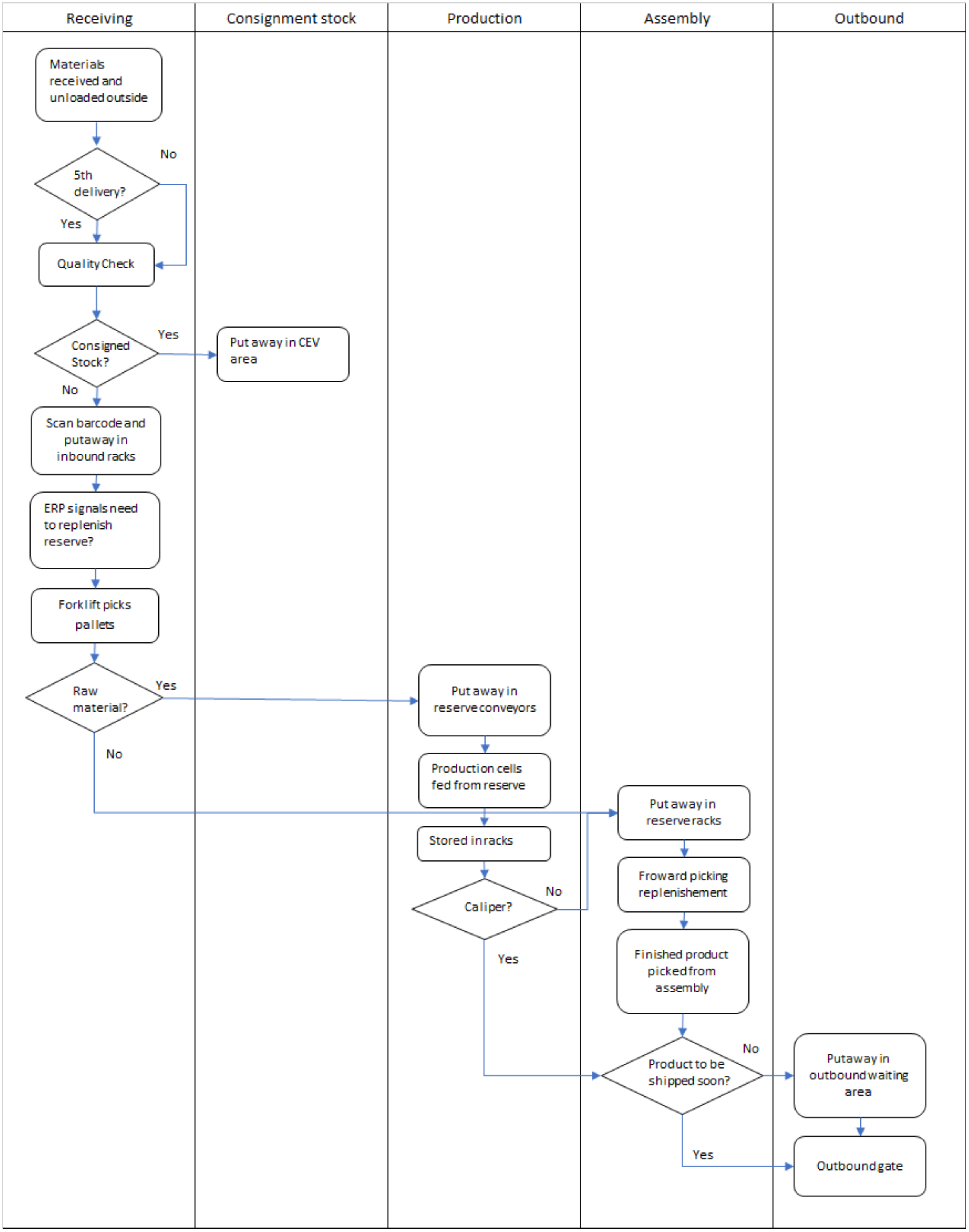
Introduction and usage:
How many AGVs does this plant have?
How long have the AGVs been operating?
In which processes do you use them? And for which tasks?
What navigation type is being used?
Do they have any kind of obstacle avoidance?
How are they AGVs programmed for guidance control? Through the ERP system?
Are the AGVs and manual handling (trucks, people) operating in the same areas?
How does the charging of the AGVs work, when and for how long are they charged?
What are the reasons for investing in them?
What kind of problems were you most concern about when implementing the AGVs?
Are the results of the implementation satisfactory, does it live up the the expectations?
Are there any benefits of which you did not think of before the implementation?

Results:
What are the contributions from the AGVs compared to normal forklifts?
If the AGV replaced personnel, what happen to the personnel?
Were they fired or moved to other tasks?
What difficulties were encountered while using AGVs?
Which processes were affected with the usage of AGVs?
Which aspects do you think are the most important to consider when implementing and using AGVs?
Did the implementation affect the staff or productivity in the warehouse?

About the future:
When are you planning to start using them again?
Are you going to invest in a third AGVs? If yes, when will it be in operation?
Would you change technical or operating aspects (E.g navigation system, guidance control etc.)?

Appendix C.

Warehousing Processes flowchart at Haldex Landskrona



Appendix D.

Vehicle Travel time and sum of loading and unloading time in minutes (t_{ij}+ lu) between locations

	A1	B1	C1	B3	D1	D2	E1
A1	-	1,937	-	-	-	2,447	-
B1	0,917	-	-	-	-	-	-
B2	-	-	1,467	1,15	-	-	-
C1	-	-	-	-	2,517	-	-
B3	-	-	-	-	-	2,07	-
D3	-	-	-	-	-	-	1,167

Appendix E.

Calculations for throughput rates for the production process

Calipers

Machine type	Number of machines	Avg Number of normal shifts	Avg Number of extra shifts	Avg Throughput per shift	Total throughput per week	Pallet qty	Total pallets per week	Pallets per hour
Hellercell	6	12	4	47	4512	32	141	1,1
Liconcell	4	12	4	94	6016	32	188	1,5
total	10	24	8	141	10528	64	329	2,6

Carriers

Machine type	Number of machines	Avg Number of normal shifts	Avg Number of extra shifts	Avg Th/machine/shift	Total throughput per week	Pallet qty	Total pallets per week	Pallets per hour
H cell 1	2	13	0	180	4680	40	117	1,1
H cell 2	1	12	0	327	3924	48	81,75	0,9
Hellercell	1	13	0	50	650	48	13,54166667	0,1
Hellercell 12&13	1	13	0	105	1365	40	34,125	0,3
2 new machines	2	13	0	100	2600	40	65	0,6
total	7,0	64,0	0,0	762,0	13219,0	216,0	311,4	3,1

Appendix F.

Calculations for the throughput rate for the assembly process

-	throughput per week	Throughput rate (brakes/h)	Customer	Pallet qty (units per pallet)	Customer demand per line	% customer over total	TR(units)/shift per customer	TR(pallet)/shift/customer	TR(pallet)/shift/ line	TR(pallet)/ hour/ line
Uranus	4400	50	S	20	2144	49%	194,9	9,7	25	3
			G	12	1630	37%	148,2	12,3		
			J	18	391	9%	35,5	2,0		
			Others	12	182	4%	16,5	1,4		
Tellus	4965	50	S	20	4965	100%	400	20,0	20	3
New assembly line	3120	30	S	20	-	-	240	12	12	2
Total	12485	130			9312				**57**	**7,2**

Appendix G.

Sensitivity analysis with respect to vehicle blocking time for scenario 1

Blocking time percentage	Blocking time (min)	Vehicle Utilization rate	Number of AGVs needed
10%	6.92	127%	2
11%	7.61	128%	2
12%	8.30	129%	2
13%	8.99	130%	2
14%	9.68	131%	2
15%	10.38	133%	2
16%	11.07	134%	2
17%	11.76	135%	2
18%	12.45	136%	2
19%	13.14	137%	2
20%	13.84	138%	2
21%	14.53	140%	2
22%	15.22	141%	2
23%	15.91	142%	2
24%	16.60	143%	2
25%	17.29	144%	2
26%	17.99	145%	2
27%	18.68	146%	2
28%	19.37	148%	2
29%	20.06	149%	2
30%	20.75	150%	2

Appendix H.

Sensitivity analysis with respect to vehicle blocking time for scenario 2

Blocking time percentage	Blocking time (min)	Vehicle Utilization rate	Number of AGVs needed
10%	11.36	208%	3
11%	12.50	210%	3
12%	13.63	212%	3
13%	14.77	214%	3
14%	15.91	216%	3
15%	17.04	218%	3
16%	18.18	220%	3
17%	19.32	222%	3
18%	20.45	223%	3
19%	21.59	225%	3
20%	22.72	227%	3
21%	23.86	229%	3
22%	25.00	231%	3
23%	26.13	233%	3
24%	27.27	235%	3
25%	28.41	237%	3
26%	29.54	239%	3
27%	30.68	240%	3
28%	31.81	242%	3
29%	32.95	244%	3
30%	34.09	246%	3