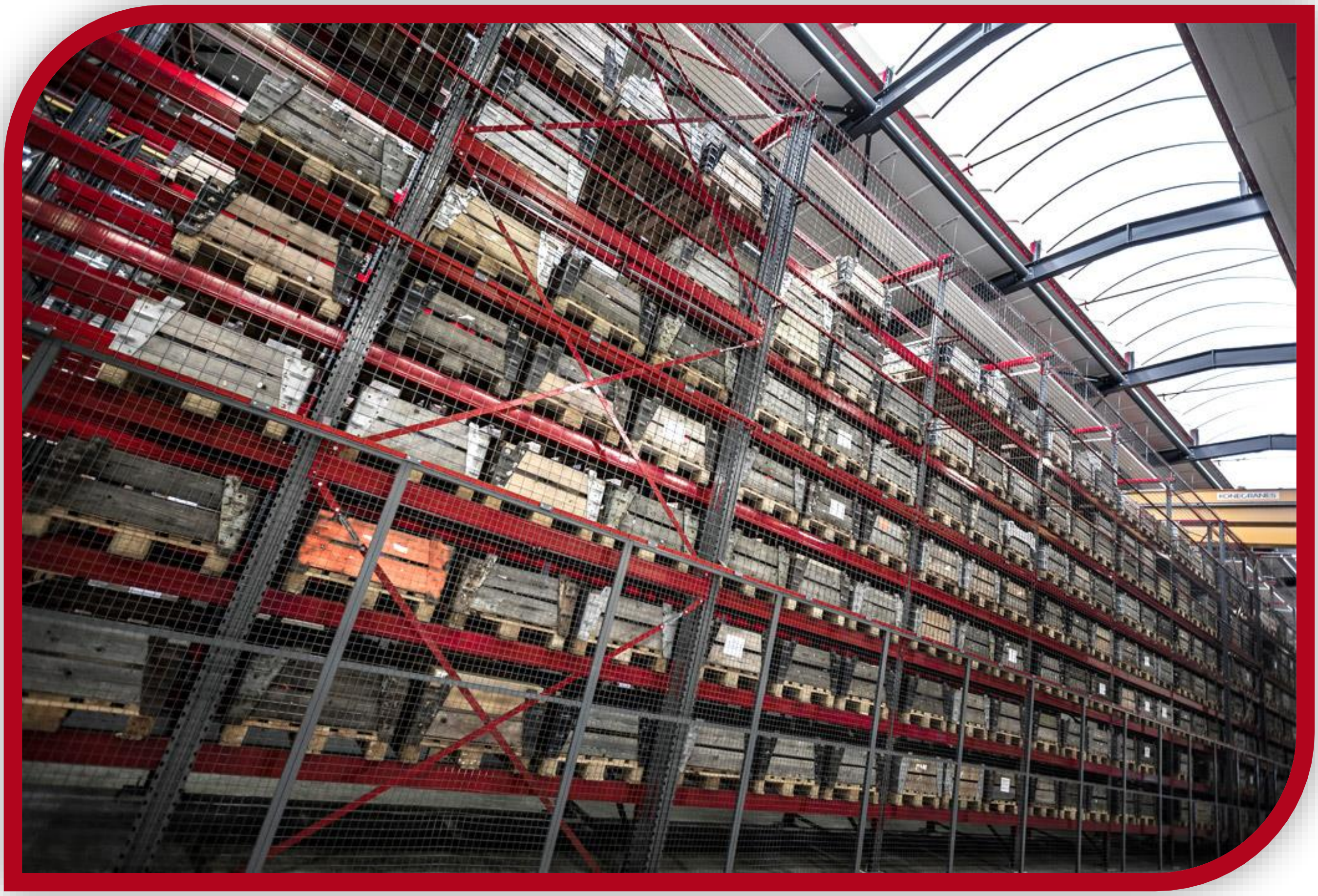
Master Thesis

October 17, 2017

Increasing Flexibility: Transition Towards Anonymous Stock

A simulation study on the flow of goods at Voortman Steel Machinery



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Industrial Engineering and Management

Production and Logistics Management

UNIVERSITY OF TWENTE.

voortman STEEL GROUP

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Management Summary

Voortman Steel Machinery (VSM) is a manufacturing company specialized in CNC controlled machinery for steel fabrication. The machines are capable of processing big and robust pieces of metal, used in the construction industry. Materials called 'buy parts' are used to produce the machines. These buy parts are purchased per project with a lot-for-lot strategy. In the warehouse, the buy parts are stored directly in a pallet dedicated to the project. The buy parts are not free to use by de Production Department, but only for the project they are ordered for. The lot-for-lot replenishment strategy combined with the project based storage is not considered flexible enough to deal with the projected growth of the company.

The objective of this research is to gain knowledge on the consequences of anonymous storage, and of inventory based replenishment, for the buy parts. The main research question is: *What are the consequences for VSM, in particular for the Warehousing Department, if the procurement of buy parts will be based on inventory levels and the storage of buy parts will be anonymous, and how should this be implemented?*

With a literature study, performance measurement is set up. The flexibility is not directly measurable. The most important performance indicators used for the performance measurement are:

- **Inventory cost.** The value of the materials present in the warehouse.
- **Productivity.** The number of actions needed per order.
- **Labor time.** The time needed in the warehouse for the flow of goods of the buy parts.
- **Warehouse utilization.** The number of store/pick cycles per storage system.

Based on literature, we suggest a new replenishment strategy and a new storage strategy. The demand per material, and the value of inventory per material, are the two criteria used for a Multiple Criteria Inventory Classification to form three groups of materials, A, B, and C. For group A materials, the suggested replenishment strategy is lot-for-lot. A fixed order period replenishment strategy is suggested for the materials in groups B and C. This is called the 'ABC replenishment strategy'. Table 1 shows the characteristics of the materials in the different groups.

Table 1 The characteristics of the materials in the three groups formed based on Multiple Criteria Inventory Classification.

Group	A	B	C
Number of materials	61	129	161
Average no. of delivery days per material	6.7	7.5	13.3
Average price per material	€ 2,213	€ 114	€ 14
Average value per purchase order	€ 7,679	€ 331	€ 44

The warehouse at VSM has two storage systems, an Automated Storage Retrieval System (AS/RS) with pallets, and a Vertical Lift Module (VLM) containing trays. From both storage systems, the AS/RS is considered as the bottleneck. The suggested storage strategy is called anonymous storage. With anonymous storage, the materials are stored in the VLM first, then picked upon request, and finally stored in a project pallet in the AS/RS.

We made a simulation model of the flow of goods in the warehouse of VSM, and used it to experiment with the suggested replenishment and storage strategies. The experiments are defined as three scenarios. Scenario 1 represents the current performance of VSM, and uses project based storage with lot-for-lot replenishment. Scenario 2 uses anonymous storage with lot-for-lot replenishment. Scenario 3 uses anonymous storage with the ABC replenishment strategy. The simulation model uses historical data containing the arrivals of 373 buy parts from the period January – May 2017 as input. Each simulation experiment takes 110 days and is replicated 20 times with different random numbers.

The results indicate that Scenario 3 has the best combination of strategies. Table 2 shows the biggest differences in the results of Scenarios 1 and 3. Compared to Scenario 1, which represents the current performance at VSM, the average value of inventory reduces with more than 15%, because the expensive materials spend less time in the warehouse. The total number of order lines reduces with more than 50%, as multiple order lines can be combined. This reduces the time needed in the warehouse with almost 50%, due to these economies of scale. The number of store/pick cycles in the AS/RS reduces with more than 55%. Next to these improvements, anonymous storage increases the flexibility at VSM.

Table 2 Results of Scenarios 1, 2 and 3 Scenario of the current situation and the suggested strategies.

Output	Scenario 1	Scenario 2	Scenario 3
Average value of inventory per day	€ 1,415,017	€ 1,151,533	€ 1,192,370
Average number of total order lines	± 4800	± 3500	± 2000
Average working time needed per day in hours	4.7	4.3	2.5
Average no. of AS/RS store/pick cycles per day	23.5	9.9	9.6
Average no. of VLM store/pick cycles per day	0	15.2	13.4

The recommendation to VSM is to do a pilot of five months with the materials used in this research. During this pilot, Purchasing should use a fixed order period for the replenishment of the materials in group C. The materials should be stored in a VLM first, and be picked upon request. Further research should include all the buys parts, and the make parts.

Preface

With this report comes an end to my period as student at the University of Twente.

I want to thank Voortman Steel Machinery for the given opportunity to conduct this interesting research. During my time at VSM I got to know many colleagues, and I really felt part of the team. I am even more grateful for the opportunity VSM offers me to start my career at their organization.

Further I want to thank my supervisors at the University for their patience and guidance during this project. I thank Peter Schuur for his guidance and interesting conversations during our meetings. I want to thank Marco Schutten for his critical questions during the last phase of my research. This was helpful, and contributed to the result.

During my study, I made some amazing friends, and without them it wouldn't have been such a nice period. Dear *Strüners*, thank you all.

Finally, I want to thank my family for their support and patience during all these years. They made it possible for me to enjoy my time, and to focus on the goal of finishing my thesis these last months.

I hope you will enjoy reading this report.

Ron Visser

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Glossary

AS/RS	Automated Storage Retrieval system.
ATO_{ED}	Adapt-to-Order in the Engineering Dimension.
BOM	Bill of Material.
CNC	Computer numerical control. The automation machine tools by means of the software controlling the machine.
COI	Cube per order index.
COL	Closest open location.
CT	Cycle Time.
DOS	Duration of stay.
ERP	Enterprise Resource Planning, digital system.
FOP	Fixed order period.
I/O	In out point.
Installed Base	Overview of the installed configuration of a machine at a customer, used for after sales purposes.
MRP	Material Requirements Planning.
MTO_{PD}	Make-to-Order in the Production Dimension.
MU	Moveable Unit.
OOS	Order oriented slotting.
PDF	Probability density function.
SKU	Stock keeping unit.
TH	Throughput.
VLM	Vertical Lift Module.
VSG	Voortman Steel Group.
VSM	Voortman Steel Machinery.
WIP	Work in Progress.

1 Introduction

In the framework of completing my master thesis of the study Industrial Engineering and Management I performed research at Voortman Steel Machinery into the flow of goods in the warehouse. This chapter introduces the research design. After the introduction of the company in Section 1.1, Section 1.2 gives a description of the project. In Section 1.3 we define the problem statement, and the objective for the research. Section 1.4 discusses the scope, and Section 1.5 presents the research questions and the methodology used to answer the research questions.

1.1 Voortman

The Voortman Steel Group (VSG) today consists of Voortman Steel Construction and Voortman Steel Machinery (VSM) (The rich history of Voortman Steel Group, n.d.). Voortman was founded in Rijssen in 1968 by the brothers Voortman and started as a business for all kinds of machinery. The company was split in two separate companies in 1978, one for steel structures and one for mechanical constructions. The companies kept on growing and in 1996 they expanded into Germany. In 2002 the business was transferred to the next generation of Voortman and since then subsidiaries in England, USA, and Asia were opened. VSG launched a new corporate identity in 2013, bringing more unity between the different companies of the VSG. Since 1995 VSM concentrates on CNC machines, which are machines controlled by pre-programmed sequences of machine commands. All the development and production is done at the headquarters in Rijssen. For sales and service there are offices located all around the world, making VSM a global player (Voortman Steel Machinery - Home, n.d.).

Figure 1-1 Voortman V630 drilling machine.

Figure 1-2 Voortman V320 drilling and cutting machine.

Today, VSM develops and manufactures advanced machinery for steel fabrication. The machinery is designed for handling big and robust pieces of metal, something an average metal processing machine is not capable of. The product range can be divided in four categories:

- Beam processing.
- Flat and angle processing.
- Plate processing.
- Surface treatment.

Figure 1-3 Voortman V550 punching and shearing machine.

The most used processing types are punching and shearing, drilling, sawing, and cutting. A few examples of the machines are the Voortman V630, a drilling machine for thick metal beams, see Figure 1-1. Figure 1-2 shows a Voortman V320, a machine used for drilling and cutting for sheet metal. The Voortman V550 is an example of a punching and shearing machine, see Figure 1-3 (Voortman Steel Machinery – Machinery, n.d.). For an overview of the total product range, see Appendix A.

1.2 Project Description

The last decade VSM has grown dramatically, and for the coming years even more growth is predicted. With an increasing organization it is a challenge to maintain an everyday high performance. The current way of ordering and handling materials is still based on the organization of a decade ago. VSM wants to reorganize their processes to deal with the expected growth.

The order process, the process from selling a machine until the delivery of the machine at the customer, has always been an Engineer-to-Order process. There was little to no standardization for the materials used in the machines. Therefore, every machine consisted of a lot of different materials. When a machine was sold and the engineering was done, all the required materials were ordered. In this way no stock was needed, and all the materials could be delivered Just-In-Time.

Since the last decade VSM designs the machines with standard modules, using standard materials. The modular design means that, for a large part of the machine, the customer order decoupling point (CODP) is shifted upstream. Rudberg and Wikner (2004) argue that the CODP can best be viewed in an engineering and a production dimension. Currently there are about 20 different machines in the catalogue and only a couple of modules are still designed and engineered to order, the other modules are 'standard'. Every customer at VSM has their own needs and wishes, so still almost every machine leaving the factory is unique. We define the CODP at VSM as Adapt-To-Order for the engineering dimension and Make-To-Order (MTO) for the production dimension (ATO_{ED}, MTO_{PD}). The new CODP is never adopted in the organization. The materials are still purchased based on the need per order, one order at a time, despite the use of standard modules.

VSM classifies the materials in *buy parts* (parts out of a catalogue), and *make parts* (parts custom made by the supplier). This separation is present from the purchasing step until the assembly. The incoming materials are stored based on the project number for which they are needed. In this way, all materials needed for the project are stored together and no order picking is needed. Also, no stock levels are needed. The buy parts are stored in an automated pallet warehouse, in a vertical lift module, or on the floor. The make parts are stored on the floor or stacked in racks.

The current process is not considered flexible enough to cope with the expected growth. The materials in the warehouse are reserved for a project and not free to use. This project based storage of the materials causes problems. An example of a situation where more flexibility is needed is: there is a high priority procurement request for a buy part needed for project A, let us say because of a shifted deadline. It is possible that this requested part is already present in the warehouse. However, this part is not free to use because it is reserved for project B. Additional handlings are needed to use the part reserved for project B for project A. If the part reserved for project B is used for project A, a new purchasing request must be made. This is to make sure all the parts for project B are available at the start of the production. Next to the new request, the initial high priority request used for project A must be cancelled to prevent unnecessary deliveries. All these handlings give a lot of room for mistakes, and make the process inflexible.

In January, VSM opened a new production location a couple of hundred meters down the road from the headquarters. At this location, the conveyor belts are produced. The conveyor belts provide the in- and outfeed of raw materials for the machines, see Figure 1-4. For this production location, the materials are ordered based on the expected demand and the materials are stored anonymously. These materials are therefore free to use for every project. VSM wants to know if it is possible to copy this way of working to the main factory. The idea is that the process becomes more flexible and this contributes to reducing the lead times of the machines.

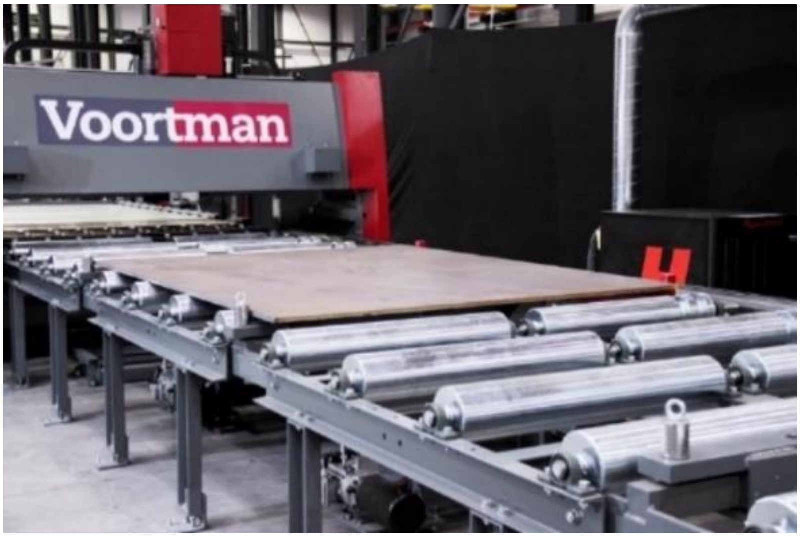


Figure 1-4 Conveyor belt for the in- and outfeed of the material.

1.3 Problem Statement and Research Objective

To streamline the research it is important that we define the real problem and set a clear objective (Heerkens & Van Winden, 2012; Verschuren & Doorewaard, 2010). VSM wants to guarantee a lead time of eight weeks for the machines. The lead time here is the time between a machine is planned and the time the machine is ready for transport. According to the project description in Section 1.2 VSM wants more flexibility regarding the use of *buy parts*. We define the following problem statement:

The current way of ordering and handling buy parts is not flexible enough to deal with unexpected planning changes, leading to difficulties in meeting the agreed lead time.

The prevailing idea at VSM is that inventory based purchasing, in combination with anonymous storage for buy parts, could help to increase the flexibility. This could also reduce the lead time of a machine or at least shift the bottleneck to another process. To find out if this idea holds we define the following objective:

To gain knowledge on the (dis)advantages of inventory based ordering for the buy parts in combination with anonymous storage for the buy parts, and a plan to implement this new way of working if it is proven to be beneficial.

1.4 Research Scope

The research is limited to the logistical flow of the materials. The actual procurement procedure is not a part of the research but a result of it. To further limit the research, we set up the following boundaries:

- Only the 'buy parts' are considered.
- The logistical flow of materials is limited to the receiving of the materials until the materials leave the Warehouse to the Production Department.
- Materials categorized as 'bulk', mainly bolts and nuts, are not considered.
- Only the production location at the headquarters is considered.
- The after sales process is left out of scope.
- The characteristics of the 'buy parts' cannot be influenced.

1.5 Research Questions

To reach the objective of this research, we formulate the following main research question:

What are the consequences for VSM, in particular for the Warehousing Department, if the procurement of buy parts will be based on inventory levels and the storage of buy parts will be anonymous, and how should this be implemented?

We use multiple questions to structure this research. The next sections present these questions with their objectives, and the methods to answer them.

1.5.1 Question 1

Section 1.2 presents only a global picture of the current situation. Question 1 has the objective to get a detailed insight in the current situation at VSM. The materials classified as buy parts are identified by investigating the different types of machines, and how they are constructed. This results in a selection of buy parts to base this research on.

The used strategy for the procurement of materials, and the flow of goods, are important to know. To gain information about the purchasing process, and about current the flow of goods, we observe the whole order process from planning until production. This gives not only insight in the purchasing procedures and in the physical flow of goods, but also in the flexibility. Chapter 2 gives answer to Question 1 and its sub questions.

Question 1. What is the current situation at VSM?

a. What are the buy materials?
b. What is the current flow of goods?
c. What processes have influence on the 'flexibility'?

1.5.2 Question 2

After gaining insight in the current situation at VSM, knowledge from literature is needed about several topics. Question 2 has the objective to gain this knowledge. To compare the current situation with other situations, performance measurement is needed. Literature about inventory management, purchasing strategies, and warehouse strategies, provides the knowledge needed to redesign the processes of VSM. Chapter 3 answers Question 2 and its sub questions.

Question 2. What is known in literature about the performance measurement, inventory management and warehouse processes?

a. Which performance indicators for warehouse operations are suited for VSM?
b. Which replenishment strategy is suited for VSM?
c. Which slotting and picking strategies are suited for VSM?

1.5.3 Question 3

The results of Question 2 can be used to redesign the purchasing process and the flow of goods at VSM. Together with the stakeholders we define performance indicators based on the findings of the literature. Question 3 is used to get insight in the current performance, and for the design of experiments. We use the results from Question 2 and knowledge of the stakeholders to draft a set of Key Performance Indicators (KPIs). The set of KPIs is used to find the current bottleneck in the process. Based on the set of KPIs and results of Question 2 different experiments can be designed. Chapter 4 answers Question 3 and its sub questions.

Question 3. What is the current performance and how can it be improved?

a. Who are the stakeholders in this research?
b. What is the current bottleneck in the flow of goods?
c. What scenarios can be designed based on the findings from literature?

1.5.4 Question 4

We use simulation to study the performance of the different scenarios. With a simulation it is possible to try out different strategies without interrupting the current processes. The visual aspect of the simulation model makes it easy to understand, and to explain to the involved stakeholders, what happens with a change in the way of working. The goal of Question 4 is to develop a simulation model about the flow of goods at VSM. Chapter 5 gives answer to Question 4 and its sub-questions.

Question 4. What should the simulation model of VSM look like?

a. How to design a simulation model?
b. What are the components of the simulation model?
c. How can we verify and validate the simulation model?

1.5.5 Question 5

The results of the simulation study are used to support the findings of this research. With Question 6 we analyze the results of the simulation study. With the KPIs developed in Chapter 4 we measure the performance of the different scenarios. Chapter 6 compares the results, and we use these results for the advice towards the direction of VSM. Chapter 6 answers Question 5.

Question 5. How can VSM improve their processes based on the results of the experiments with the simulation model?

a. What replenishment strategy is recommended for VSM?
b. What warehouse strategy is recommended for VSM?

In Chapter 7 we summarize the research and present the conclusions and recommendations to VSM. Chapter 7 provides also a discussion on the results and ideas for future research.

1.6 Deliverables

The main deliverable of this project is an overview of the consequences of anonymous storage and inventory-based ordering for the buy parts at VSM. This overview is based on the experiments with the simulation model developed in this research. Next to the simulation model, a replenishment and warehouse strategy is suggested. We give recommendations how to benefit from the results of this research. To summarize the deliverables:

- Simulation tool for the flow of goods in the warehouse at VSM.
- Replenishment strategy.
- Warehouse strategy for the flow of goods.
- Recommendation plan.

2 Current Situation

This chapter answers question one, '*What is the current situation at VSM?*'. In Section 2.1 the buy parts that are subject of this research are identified. Section 2.2 discusses the flow of goods at VSM. The digital systems VSM uses are discussed in Section 2.3. Section 2.4 describes processes related to the flexibility. This chapter ends with a conclusion in Section 2.5.

2.1 Buy parts

This research focusses on the procurement and flow of goods of the buy parts used to manufacture the machines VSM produces. VSM uses more than 10,000 different materials to produce their machines. In this research we only consider a small selection of all the materials. This section presents the selection procedure and the characteristics of these materials.

2.1.1 Machines

As mentioned in the introduction, VSM produces a range of advanced machinery. In the period of 2013 to 2016 a total of 36 different types of machines were sold. This number is without customer specials and can be divided in 11 categories. Table 2-1 shows the categories and the number of different machines per category. The total and average number of sold machines per year are displayed in Table 2-1 as well.

Table 2-1 Overview of the number of sales per product category.

[redacted]

Confidential

[redacted]

2.1.2 Bill of Material

The machines are build up from modules. Every machine has a few basic modules which are the same for every customer. There are also modules for which the customer must choose a certain configuration. Based on the customers' wishes these customer-specific modules are engineered. The materials needed for the modules are given by a Bill of Material (BOM). To get a better understanding of the BOM we take a closer look at the data structure in the ERP system. Figure 2-1 shows how an 'order' of a machine is built up. Every sold machine is assigned to a project number, a so called '1 million order'. Under this '1 million order' the individual modules are placed as '2 million orders'. Some of these 2 million modules are part of the basic configuration of the machine. These are the ones on the right side in Figure 2-1. All the modules consist of a list of materials, identified with their own unique 'xxx-xxxx' number.

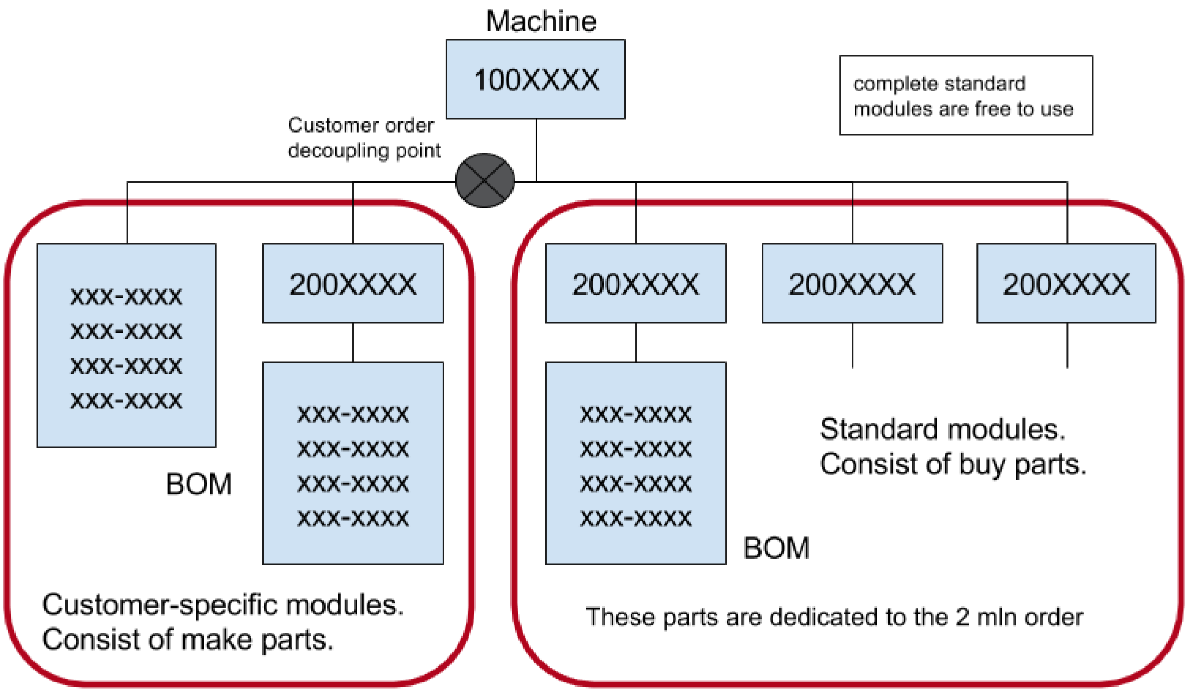


Figure 2-1 Data structure of an order in the ERP system displayed as a Multi-level BOM.

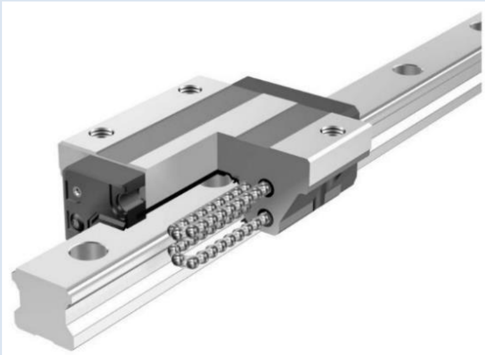
Table 2-2 shows the number of available modules per machine for the three fast moving machines, the V304, V600, and V808. Because of the many different standards for the electricity network around the world, there is a big number of variable modules for the V304. There are for example more than forty different configurations of the power supply for this machine. Depending on the supplier, and on the standard in the country where the machine will be operated, a power supply is chosen.

Table 2-2 Overview of the number of modules for the fast movers.

Machine	Standard	Variable available	Variable used last two years	With buy parts
V304	7	203	64	57
V600	5	13	12	6
V808	9	41	19	16

To reduce the big number of modules we only consider the modules that are produced at least 10 times over the last two years, and have at least 10 buy parts in the BOM. For example, a power supply is directly purchased and does not require additional assembly. Other modules, for example the gantry of the V304, require a lot of different materials that are assembled on a big frame. The materials that we use in our research are all the buy parts from 13 modules, resulting in a list of 373 materials (see Appendix A for the list of modules). A few examples of these buy parts are shown in Table 2-3.

Table 2-3 Example of buy parts.

Item code	Item description	Example
004-2802	Ball Guide Rail HGR35T L=1930 E=45	
003-2601	Litze 16^2 L=800MM 2xM6	
003-6779	Mounting Bracket KMA 26001.07.12.C	
004-3353	RJ 45 90° Angled Connector	

The considered buy parts are present in the at most four different BOMs. That is, they are used in at most four unique modules. Most buy parts are used in only one module. Figure 2-2 shows the percentages of the buy parts per number of modules that use that part. From the 373 materials 88,7% are unique, they are used in just one module. For a detailed overview of the numbers, see Appendix A.

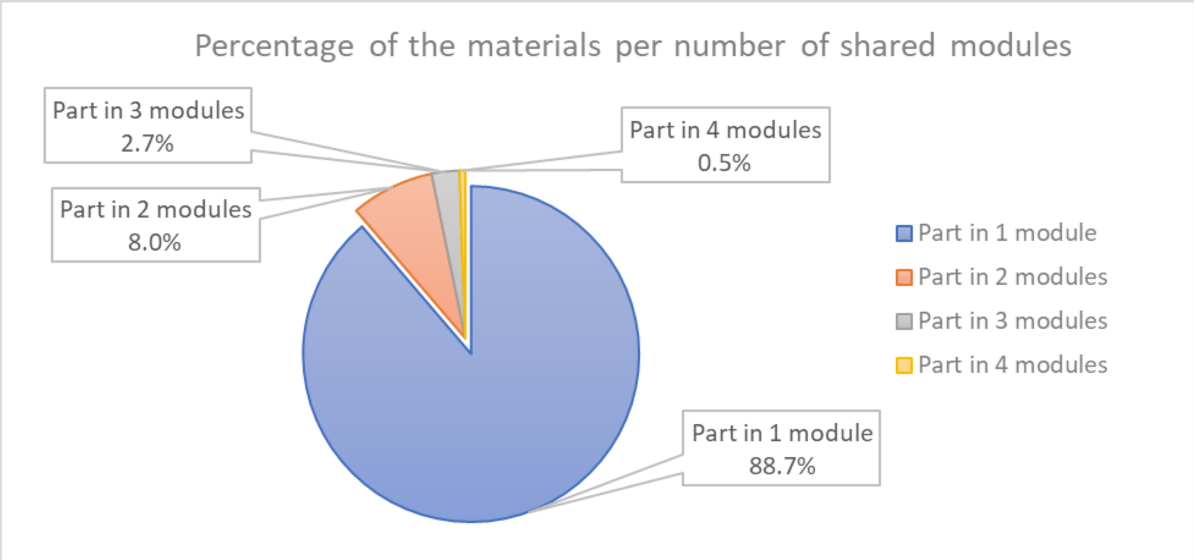


Figure 2-2 Pie chart showing the percentage of materials per number of modules using the material.

2.2 Flow of Goods

A part of the objective of this research is to find out what the consequences of a change in the flow of goods are. This section describes the current flow of goods, starting with a description of the order process at VSM. After the description of the order process, Section 2.2.2 discusses the physical flow of goods at VSM.

2.2.1 Order Process

The order process starts at the Sales Department and ends when the machine is installed at the customers facility. Not all departments involved in the order process are relevant in the context of this research. The departments that are relevant are Data Management, Purchasing and Warehousing. The relevant part of the order process, see Figure 2-3, starts at the Data Management Department. At this stage in the order process, the engineering is finished and the order is already entered in the ERP system. The data engineer makes a Material Requirements Planning (MRP) and checks if there is inventory on hand for some of the required materials. If, for some reason, there is stock available for some materials, those materials are removed from the purchase request to prevent unnecessary inventory. The data engineer then approves the BOM. After the BOM is approved, Purchasing gets a request for the procurement of the materials.

From this moment, Purchasing orders all the materials needed for the order, in the right amount, for the right point in time. At VSM, inventory is a 'dirty' term, that is why Purchasing uses this so called 'lot-for-lot' strategy, in which the exact amount needed is ordered. The delivery date for the materials is at least one week prior to the start of the production. In the ERP system, the purchased materials are directly assigned to the order, and therefore not free to use for other projects.

At this stage the separation between buy and make parts becomes visible. There is one employee for the procurement of buy parts, and one employee for the procurement of make parts. The buy parts employee purchases all buy parts needed for an order, not really considering the date the materials are needed. The priority is to finish every order and then move on to the next order. Otherwise the 'to do list' fills up with a lot of 'unfinished' orders.

The deadline for receiving the materials is one week prior to the start of the assembly. However, most materials are only needed from the first or second week after the start of the assembly. This causes a high work in progress in the warehouse. There is a project running at VSM to get more steps in the assembly. The different steps can then be used as deadline for the procurement, instead of the one week prior to the start of the assembly. Because this project is just started, it is left out of scope in this research.

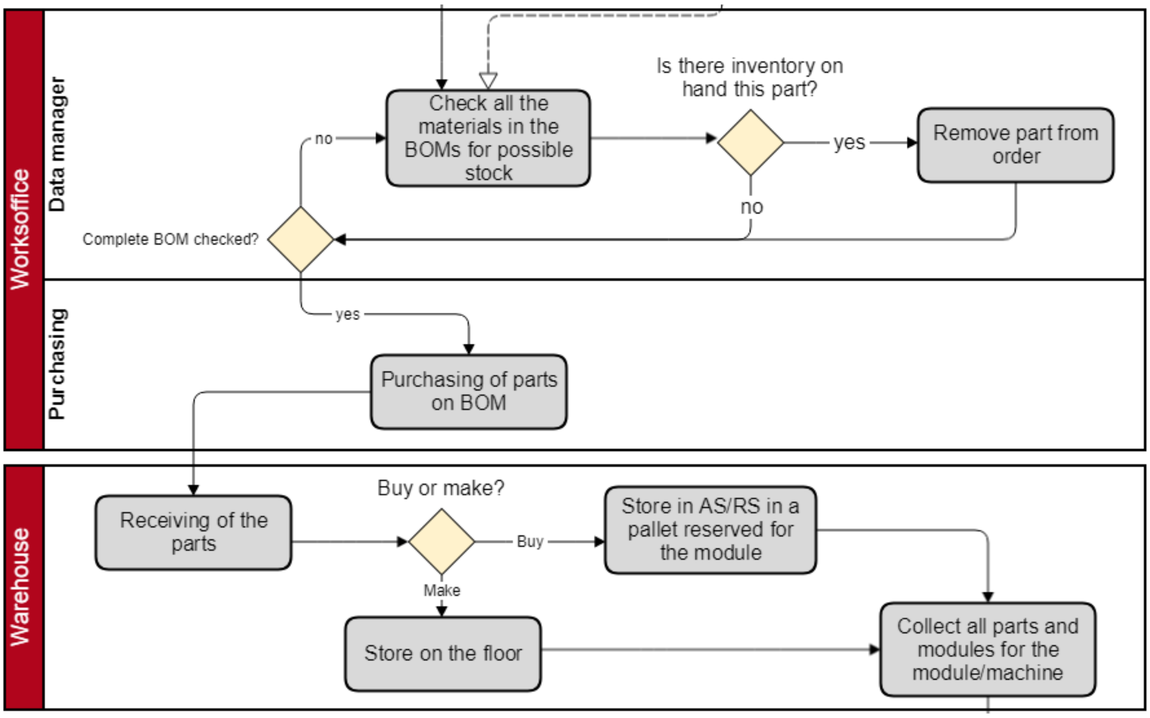


Figure 2-3 The relevant part of the order process for this research.

The next step in the order process takes place at the Warehousing Department. Here the materials arrive and are stored until they are needed for the production. The relevant part of the order process ends when the Production Department gives a signal they want to start with the assembly of the order. The materials needed for the assembly are requested from the Warehouse, and delivered to the work floor. Section 2.2.2 discusses the physical flow of the materials at the Warehouse Department. A figure of the complete order process, including the irrelevant departments, is given in Appendix B.

2.2.2 Warehouse

At the Warehouse Department the incoming materials are received, checked and prepared for storage, stored, and eventually gathered for production. The buy and make parts are both received at a different section of the factory. Figure 2-4 shows the floor plan of VSM. The blue rectangle indicates the area where the make parts are stored. The buy parts are stored in the are marked with the red rectangle. The blue and red rectangle together cover the total area reserved for the Warehousing Department at the headquarters of VSM.

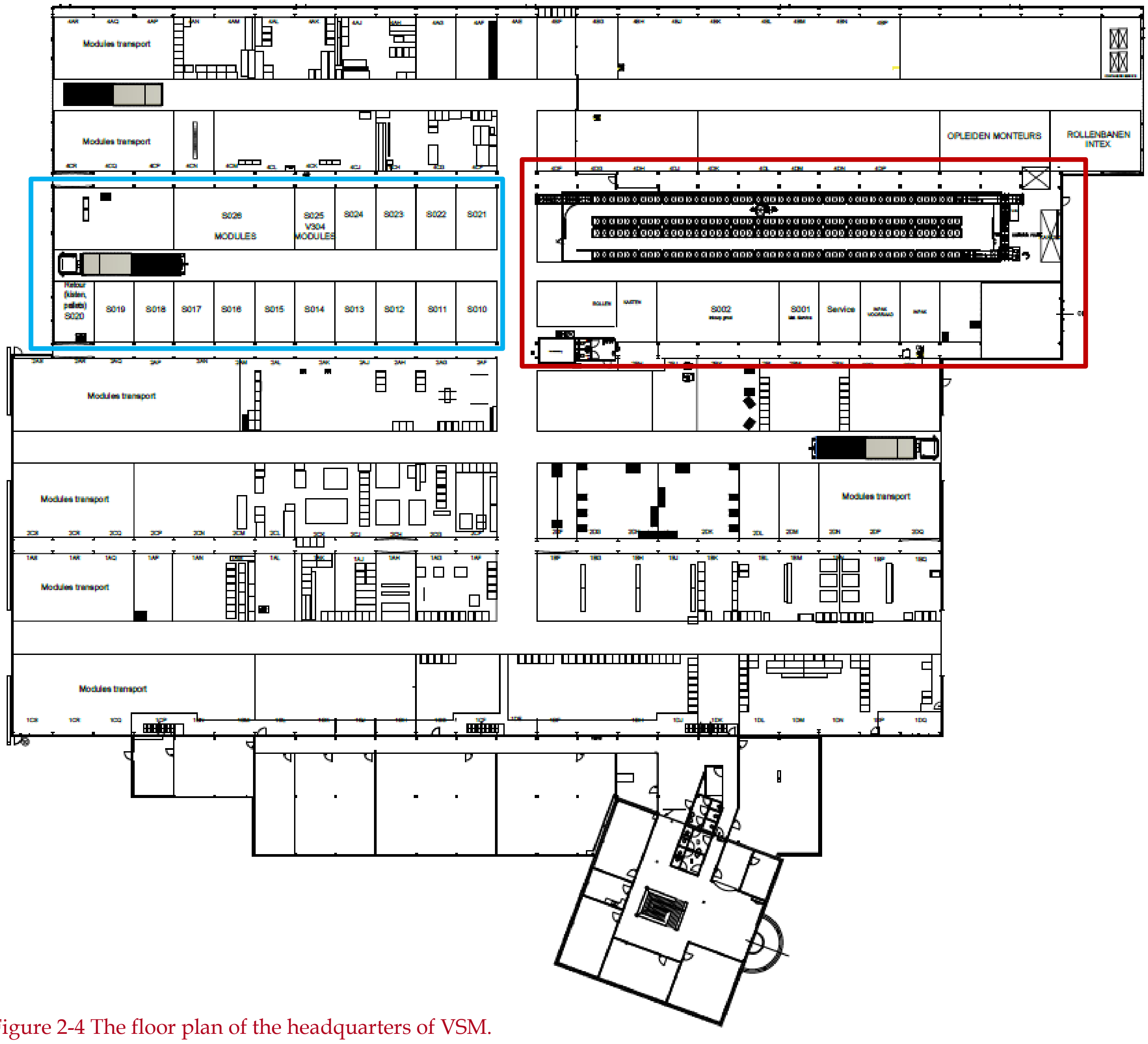


Figure 2-4 The floor plan of the headquarters of VSM.

Figure 2-5 shows the area used for the buy parts in more detail. The flow of goods takes place in this area. Suppliers deliver the buy parts at the blue square on the right in Figure 2-5. The big and lumpy materials, such as electrical cabinets, are directly stored on the floor in the green rectangle. The rest of the received materials are temporarily stored on the floor at the yellow square. Here, an employee unpacks the materials, and checks if the order is complete. The materials are then sorted, and stored on a moveable table. Another employee registers the materials in the ERP system. The moveable table with the materials is then moved to the store/pick location, at the orange rectangle.

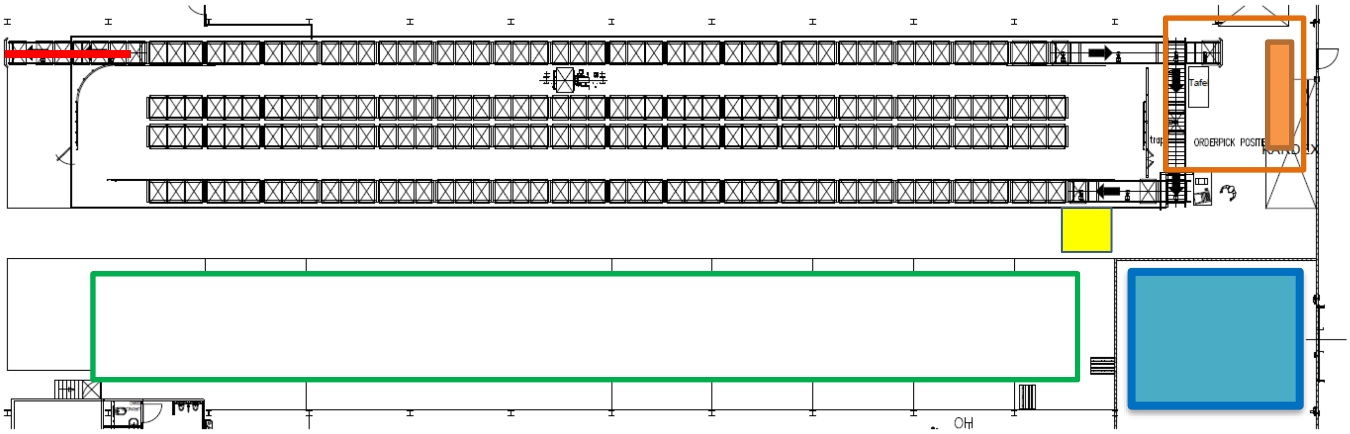


Figure 2-5 Floor plan of the storage locations for the buy parts.

At the store/pick location there are two storage systems to choose from. The first one is the Automated Storage/Retrieval System (AS/RS). The AS/RS is the area with the black crossed boxes in Figure 2-5. The second storage location is a Vertical Lift Module (VLM). The VLM is marked with the filled orange rectangle. The ERP system tells the employee which storage location to use. The next two subsections describe both storage systems in more detail.

AS/RS

The part with the crossed boxes in Figure 2-5 is the AS/RS. This is a closed system in which pallets are stored in a rack. The red line on the left side of Figure 2-5, indicates the in/out point (I/O) of the closed AS/RS system. Here, empty pallets enter the system, and full pallets leave the system to the work floor. An automated crane, travelling along a track, stores and retrieves the pallets. The AS/RS has a capacity of 1337 pallets. It is possible to store seven pallets above one another, at 45 locations next to each other, on both sides of the two aisles. The two top locations are bigger and can store pallets with a double edge, the other locations store pallets with only a single edge. Around 1025 of the 1337 pallet locations are used, leaving space to relocate the pallets. Figure 2-6 gives a schematic view of the AS/RS and its store/pick location.

The blue crossed boxes in Figure 2-6 represent the 45 storage locations along the aisles. The orange colored boxes represent the conveyor belts. Each conveyor belt is depicted with its own letter, and every letter indicates an available pallet place on the conveyor belt. So, conveyor 'B' has a capacity of three pallets. The conveyors in the right corners, named 'C' and 'G', can transport the pallet in two directions, enabling the transport of the pallet trough the corner.

To store a material in the AS/RS, the crane retrieves a pallet from one of the 'crossed blue boxes' and places it on location 'A'. The pallet is then transported along the conveyor belts to location 'E'. This is the store/pick location where the employee can store the part in the pallet. See Figure 2-7 for a photo of the store/pick location. After the store/pick activity is completed, the pallet is transported along the conveyor belts to location 'K'. The crane picks up the pallet from 'K', and stores it in the closest open location (COL), in one of the crossed blue boxes.

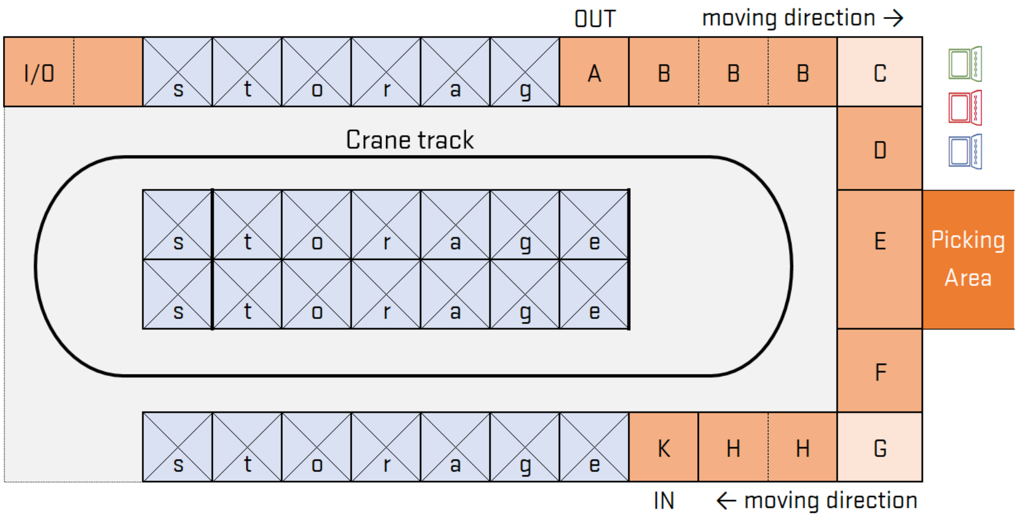


Figure 2-6 Top view of the AS/RS with the work station.

In the current situation, every pallet is assigned to a project number, and to an assembly step. This assembly step is either 'Mechanical' or 'Electrical'. The pallet is physically marked with a paper stating the project number. At the start of the assembly, Production requests the pallets with the needed materials. The pallets assigned to the requested project are retrieved from their storage location, and transported to the In/Out point (I/O) of the AS/RS. From there a forklift transports the pallets to the work floor. Because the materials are sorted as they enter the AS/RS, no additional picking is needed to collect all materials for a project.

Figure 2-7 The pick location at the AS/RS.

VLM

During the execution of this research there are two VLMs present in the Warehouse. Figure 2-5 displays the VLMs on the right side, in the filled orange rectangle. The amount of floor space occupied by the VLMs is clearly only a small percentage of the total warehouse. A VLM is a closed system containing 60 trays that are vertically arranged in two columns, with a lift in between both columns. The trays in the VLM are used for the storage of materials. Figure 2-8 gives a side view of a VLM. This figure shows the trays, and the movements the trays make during the storing activity. The lift is present in the grey column, enclosed by the two blue storage columns. The trays are stored in these blue columns.

To store a material in the VLM, the lift retrieves a tray from one of the two storage columns. This movement is represented by the arrows marked with ‘s/r’. The lift, carrying the tray, then moves in a vertical direction to the I/O. This movement is represented by the arrow marked with ‘Y’. At the I/O the tray is presented to the employee. This is a horizontal movement represented by the arrow marked with ‘X’. See Figure 2-9 for a photo of the I/O point.

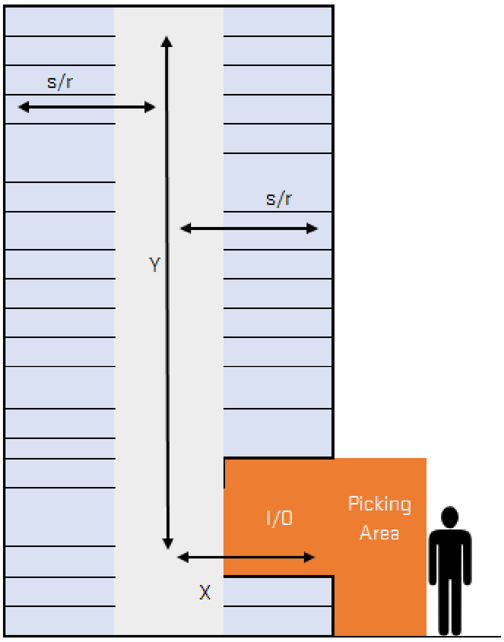


Figure 2-8 Side view of a VLM and its picking area.

Figure 2-9 A tray in de I/O point of a VLM.

When the tray is presented, the employee can store or pick materials. Every tray has a unique layout of storage locations. The white dividers in Figure 2-9 indicate the different locations. As one can see not all locations have the same size. A red light indicates the right location to the employee when the tray is in the I/O location. After finishing the picking activity, the tray is taken in and stored in the closest open location. The height needed for each tray is not fixed, but depends on the materials stored in the tray. The VLM determines the height needed based on the highest item in the tray.

There are a few buy parts that are ordered based on an inventory level instead of using a lot-for-lot strategy. These parts are stored in the VLMs to be picked later. Most of these parts are categorized as bulk items, such as bolts and anchors. Next to the buy parts the VLM is used for the storage of spare parts. The spare parts are used by the After Sales Department. After Sales is also responsible for the replenishment of the spare parts.

The spare parts are buy parts as well. To prevent mixing up the spare parts with the regular buy parts, the spare parts are assigned to a different factory in the ERP system. In practice, spare parts and buy parts are both in the same physical location. For example, for one part, say a bearing, five units are present in the VLMs. Three out of the five units are 'owned' by After Sales, and not free to use for production. Only 4% of the different materials present in the VLMs is used by both After Sales and Production. Approximately 88% of the different materials stored in the VLMs is used by After Sales, this is about 74% of the total number of units present in the VLMs.

2.3 Software

At VSM there are multiple software packages in use to support the communication and administration. This section describes the different packages and their function.

2.3.1 Planning

Rob-ex, the planning software, is the starting point of an order. With this software the different production steps, such as mechanical assembly, electrical assembly, testing, loading, and installing are scheduled. During the scheduling, the available workforce is visible. Once an order for a machine is scheduled, Data Management can import the order in the ERP system.

The planning software provides the to do lists for the employees at the offices. All the necessary steps for an order, with the right due dates, are visible in the to do list. This makes it is easy to prioritize the tasks.

2.3.2 Enterprise Resource Program

The most important software used is the Enterprise Resource Program, called SAP. In this program all the information regarding orders, materials, finance, inventory, etc. is stored. For this research, only a small part of the ERP is relevant.

The Purchasing Department uses the ERP for the procurement of the materials. This is an almost automated process. The ERP gives the needed order quantity automatically, and automatically selects the preferred supplier. With just a few clicks the procurement request is executed.

The main data we use from the ERP are the BOMs of the machines, and the information of the materials. Every material has a lot of characteristics such as price, measurements, supplier, preferred order size, etc. Another important set of data the ERP system provides is the order history. Next to that the ERP system provides information about stock levels, and about the preferred storage locations per material.

2.3.3 Warehouse Management System

The Warehousing Department uses two different Warehouse Management Systems (WMS), one for the AS/RS and one for the VLMs. The WMS are used for the administration of storage locations, and facilitates the order picking process. The software is linked to the ERP system to share the information on stock levels. Incoming goods have the order number used by VSM stated on the delivery note.

In the ERP system, these incoming materials are marked as received, accordingly the WMS determines the storage location for these materials.

2.4 Flexibility

Section 1.2 mentions the inflexibility of the current process. To gain more insight in the flexibility, we describe some processes and actions relating to the flexibility. These processes and actions are subject of multiple discussions on the work floor. Most of these processes are unwanted, and only exist because of errors being made.

2.4.1 Production order

A production order lists all the materials needed during the assembly. The assembly is split into different steps: mechanical assembly, electrical assembly, rework, and loading. If the customer makes a change in his configuration, for example a filter 40 Hz instead of 50 Hz, multiple actions are needed to make sure no unnecessary costs are made. If the 50 Hz filter is already ordered, this item cannot be cancelled from the production order until the item is received and the administration is done (the receipt is processed). Then the 50 Hz filter can be transferred to the inventory, causing additional unwanted costs. In the meantime, another customer may need a 50 Hz filter. Because the 'cancelled' filter is not visible as stock, a new filter is purchased. The 'cancelled' 50 Hz filter will still be delivered, making it unwanted inventory. If the filter inventory stays untouched it might become obsolete. This is a devious process that would become simpler if ordered materials are not directly linked to an order.

Production orders can require up to twelve project pallets full of materials. Depending of the sequence of arrival, a project pallet contains few or many materials. If small parts arrive first, the bigger parts cannot be stored in the same project pallet, as it would damage the small parts. If the Warehouse could determine the sequence of storing materials in the project pallets, the project pallets would be filled efficient, possibly reducing the total number of project pallets needed for a production order.

In the current situation, all the project pallets of a production order are delivered at the work floor at the start of the assembly. The AS/RS has no priority rules for the crane missions. While the crane is busy with retrieving the project pallets of the production order, no other pallets are transported to the pick location, and the store/pick activity cannot continue. During an observation of the AS/RS, the conveyor belt at the picking location was full, but the crane continued transporting the project pallets needed for the production order to the I/O point. During this time, the storing and picking activities could not continue. If the WMS would have a priority setting the employee would be able to continue its picking activities.

2.4.2 Return process

During the production of a machine it sometimes occurs that the machine is fully assembled, but there are materials left over. The cause could be an error in the BOM, a mistake made in the Warehouse, or a wrong assembly. The left-over material is stored in the Warehouse, but the administration of this procedure requires a lot of actions. This return process is a process that exists because mistakes are made. A root causes analysis of the mistakes should eliminate future mistakes.

While the return process is present, it would be easier if the materials in the warehouse are not directly linked to an order, but are stored anonymously.

2.4.3 Rework

Some fragile materials break during the assembly. These materials need to be replaced with new ones. It could be that the needed material is present in the warehouse. But in the current situation this part cannot be used as it is reserved by another order. When this happens the Purchasing Department is informed. Purchasing makes a high priority request at the supplier, and the broken material is replaced on a short notice. It is obvious this process generates a lot of additional costs for the organization. If materials are stored anonymous, less high priority costs need to be made. Materials are then free to use when needed.

2.4.4 Installed base

For every sold machine, a list of all the installed components is composed, the so called 'installed base'. This is basically a list of all the parts in that specific machine. The installed base is important when a customer needs service or maintenance. In the current situation, some materials are ordered in a package and only the material number of the package is noted in the installed base. The composition of these packages may change over time. As the material numbers do not change, it is hard to track down the exact materials installed on a machine.

In a situation where the purchased materials are stored in an anonymous inventory, this problem would not exist. When the materials are requested for the production, the separate materials are added to the installed base, instead of the package. This would lead to more flexibility regarding possible changes in the production process.

2.5 Conclusion

This chapter describes the current situation at VSM, and the buy parts we consider in this research. Purchasing uses a lot-for-lot strategy for the procurement of the materials. The materials are stored in the warehouse until the Production Department needs them. The warehouse contains two automated storage systems, the AS/RS, and the VLM. Most of the buy parts are stored directly in the AS/RS in a project pallet, combing the storing and picking activity. This project based storage of materials has influence on the flexibility at VSM. Section 2.4 discusses processes related to the flexibility. The flexibility is not directly measurable, but is certainly related to the overall performance. In Chapter 3 we use literature to define how we can measure the performance of VSM. Chapter 3 describes replenishment strategies, and warehouse strategies, suitable for VSM.

3 Theoretical Framework

Now that the current situation is described, performance measurement is needed to compare different replenishment, and warehouse strategies. This chapter answers Question 2, *What is known in literature about the performance measurement, inventory management and warehouse processes?'*. Chapter 3 starts with a review of possible performance indicators for warehouse operations in Section 3.1. Section 3.2 reviews different inventory models and purchasing strategies used in literature. In Section 3.3 strategies for the storage of buy parts are discussed. We summarize the findings of the literature study in Section 3.4.

3.1 Performance measurement

To compare different scenarios for the flow of goods of the buy parts, performance analysis is needed. Lu and Yang (2010) define performance analysis as 'the measurement and comparison of actual levels of achievement of specific objectives'. Frazelle (2002) states the performance measurement of warehouse operations is most often divided in productivity, quality and cycle time. Staudt, Alpan, Di Mascolo, and Rodriguez (2015) performed a literature review on the performance of a warehouse in a make to stock (MTS) environment. Next to the productivity, quality, and cycle time, they also look at the cost dimension for warehouse operations. Staudt et al. (2015) use the definition of Van den Berg and Zijm (1999) for the warehouse operations: receiving, storage, order picking, and shipping. With their literature review Staudt et al. (2015) give an overview of the most commonly used performance indicators per dimension, see Table 3-1. In the cost dimension, few indicators are used. They note that the cost dimension for operational activities can be complicated, and time consuming, to measure. The term flexibility is vague and not directly measurable according to Staudt et al. (2015).

Caplice and Sheffi (1994) discuss common mistakes that are made regarding the use of performance indicators. They categorize these mistakes in four categories:

- **Under determination**
  Not all parts of the process are measured.
- **Comparability**
  The performance measure is not directly comparable between orders or periods.
- **Measurement error**
- **Human behavior**
  The performance measure leads to incentives that create unwanted human behavior.

Caplice and Sheffi (1994) propose eight criteria to score a performance indicator. These criteria are:

- Validity.
- Robustness.
- Usefulness.
- Integration.
- Economy.
- Compatibility.
- Level of detail.
- Behavioral soundness.

Table 3-1 Indicators for performance of warehouse activities, adapted from (Staudt et al., 2015).

	Dimensions	Time	Quality	Cost	Productivity
Activity – specific indicators	Receiving	Receiving time			Receiving productivity
	Storage	Put away time	Storage accuracy		
	Inventory		Physical inventory accuracy; Stock-out rate	Inventory cost	Inventory space utilization; turnover
	Picking	Order picking time	Picking accuracy		Picking productivity
	Shipping	Shipping time	Shipping accuracy; Orders shipped on time		Shipping productivity
	Delivery	Delivery lead time	Delivery accuracy; On-time delivery; cargo damage rate	Distribution cost	Transport utilization
Process – Transversal indicators	Inbound Processes	Dock to stock time; queuing time	customer satisfaction; scrap rate	Cost as a % of sales	Throughput
	Outbound Processes	Order lead time; queuing time	Order fill rate; perfect orders; customer satisfaction; scrap rate	Order processing cost; Cost as a % of sales	Outbound space utilization; throughput
Resource related indicator	Labor			Labor cost	Labor productivity
	Equipment and building	Equipment downtime		Maintenance cost	Warehouse utilization

3.2 Inventory Management

The performance measurement is necessary to compare different replenishment strategies. Replenishment is a subject in the field of Inventory Management. Inventory management is covered in multiple fields of study. Not only production companies, but also organizations such as pharmaceutical companies, and hospitals use inventory management. Not everyone agrees on the importance of using inventory. Kassali and Idowu (2007) state that keeping inventory is a business activity that involves costs and risks. However, according to Gallmann and Belvedere (2011), keeping inventory is a key to achieve excellent service levels.

3.2.1 Order Quantity and Timing

Kassali and Idowu (2007) mention that there are costs involved in keeping inventory. The involved costs for dealing with inventory are:

- **Ordering costs.**
  These are the fixed costs that are made for each order of a material. This includes the time an employee spends on making the order. The ordering costs are independent of the order size.

- **Unit purchasing costs.**
  This is the price that must be paid for a certain material. The unit purchasing costs also includes the shipping costs for the transportation between the supplier and the receiver.
- **Holding costs.**
  The holding costs are the costs for keeping inventory of a material during a period. This includes the time needed to process the material in the warehouse. The occupied space by the material is also part of the holding costs.
- **Shortage costs.**
  The shortage costs are the costs that must be made when an item is not present at the time it is needed. This includes costs for high urgency orders, and the costs for the time the production cannot be continued because the item is missing.

These costs are important for determining a replenishment strategy. In literature, different inventory models are used as a replenishment strategy. According to Winston and Goldberg (2004) inventory models answer two questions:

- When should an order be placed?
- How large should each order be?

Hopp and Spearman (2011) state that lot-for-lot, the strategy VSM currently uses, is the simplest replenishment strategy for MRP. The order should be placed at a point in time, such that the needed materials arrive on time. The order quantity should equal the amount needed. This strategy is consistent with the Just-In-Time philosophy, only order what you need when you need it (Hopp & Spearman, 2011). Another easy lot-sizing rule for MRP is fixed order period (FOP). With the FOP rule the net requirements are combined for P periods. The answer to the question '*when should an order be placed*' when using FOP is 'periodically'.

Determining when an order should be placed can also be done continuously by evaluating the inventory levels. This is only possible if inventory is being kept. The inventory level at which an order should be placed is the reorder point. In case of a stock-out, there are two possibilities. Either there are lost sales, or the stock-out causes a back-order. In the so called back-ordered case, a tradeoff between holding costs and shortage costs should be made (Winston & Goldberg, 2004). If necessary one can use safety stocks to make sure that no stock-out occurs between the time the order is placed and the arrival of the order.

For the determination of the order quantity different strategies are available. One easy strategy is using a fixed order quantity (FOQ). Probably the most famous formula in inventory management to determine the order quantity is the economic order quantity (EOQ). It is known as the formula of Camp (1), but it was first developed by F.W. Harris in 1915 (Winston & Goldberg, 2004).

$$Q^* = \sqrt{\frac{2DK}{h}} \tag{1}$$

In Equation (1), Q^* is the optimal order quantity to minimize the total annual cost, D is the annual demand, K is the fixed cost per order and h is the annual holding cost per unit. The EOQ assumes a constant demand over time, but in production environments the demand is rarely constant.

3.2.2 Inventory classification

It can be complicated to manage the inventory of many materials. Characteristics such as demand, value, and size are different for most materials. A widely used strategy in inventory management is to classify materials into groups. In this way, the important materials are managed closely, and less time is spent on the less important materials.

The most widely adopted way to classify materials in different groups is by performing an ABC analysis (Cakir & Canbolat, 2008). ABC analysis is based on the Pareto principle that roughly 80% of the effects come from 20% of the causes. Historically most ABC analyses are done with just one criterion, the value per time frame usage (dollar-usage) (Flores & Whybark, 1987). Today Analytic Hierarchy Process (AHP) is a common used technique for inventory classification (Cakir & Canbolat, 2008). This technique uses multiple criteria. Ramanathan (2006) proposes a weighted linear optimization methodology for the multi-criteria inventory classification. He also lists criteria used in literature for multi-criteria inventory classification. The criteria are:

- Inventory cost
- Part criticality
- Lead time
- Stock ability
- Obsolescence
- Substitutability
- Number of requests for the item in a year
- Scarcity
- Durability
- Repair ability
- Order size requirement
- Demand distribution
- Commonality
- Stock-out penalty cost

The common strategy is to score materials on each criterion individually first. For the final classification, the combination of scores per criteria determines the group. Table 3-2 gives an example of a classification based on two criteria: a material classified as B with Criterium 1, and as A with Criterium 2, is classified as A with both criteria.

Table 3-2 ABC classification with two criteria.

		Criterion 1		
		A	B	C
Criterion 2	A	A	A	B
	B	A	B	C
	C	B	C	C

3.3 Warehouse Strategies

The replenishment strategy determines the arrival process in the warehouse. The warehouse strategies for storage and picking match with the replenishment strategy. This section discusses several storage strategies, and picking strategies to use in the warehouse.

Since the industrial revolution people started using warehouses to store materials. There are warehouses used by multiple companies at the same time, providing a temporary storage location for the transported goods. There are also smaller warehouses, for example within production facilities such as VSM, where raw materials or parts are stored. The warehouse activities in the flow of goods, discussed in Section 2.2, can be categorized as receiving, putting away, storage, picking, and delivery activities. As Park (2012) mentions, the put away, storage, and order picking activities should be considered simultaneously in both the design, and the operation of a warehouse.

3.3.1 Storage

In general, literature about warehousing operations talks about stock keeping units (SKU). This is the smallest physical unit of a product that is tracked by the organization (Bartholdi & Hackman, 2016). In this research, the SKUs are the buy parts. The detailed lay out of the storage locations and the assigned SKUs is called a 'slotting'. There are two basic storage strategies for assigning SKUs to a location: dedicated and combined storage. A storage strategy is considered optimal if it minimizes the average time required to store and retrieve a load while satisfying the various constraints place upon the system (Marc Goetschalckx & Ratliff, 1990).

The first strategy, dedicated storage, means a location is reserved for one SKU. This has advantages for the order picking process, fast movers can be stored at a closer distance, and the employees know the locations of the SKUs. The downside is that the space utilization is low, over time the used capacity per location is low.

With the second strategy, combined storage, a SKU can be stored in multiple locations. If a location turns empty it can be used for another SKU, realizing a better space utilization compared to dedicated storing. Combined storage is more complex to manage, and the order picking is harder for the employees compared to order picking with dedicated storage. Both the dedicated and combined storage strategies can be combined into a hybrid strategy, called class based storage. With this strategy, a group of SKUs is dedicated to a group of locations. Table 3-3 lists the pros and cons of the different storage strategies (Accorsi, Manzini, & Bortolini, 2012; Bartholdi & Hackman, 2016; Park, 2012).

Table 3-3 Pros and cons of different storage strategies.

Storing strategy	Dedicated	Combined	Hybrid
pros	Efficient manual order picking; Easy to manage	More space efficient than dedicated storage	Easy order picking
cons	Space inefficient; inflexible	Complex to manage; Longer put away time	Hard to manage

For dedicated storage, there are different strategies to match a location with a SKU. Most strategies are based on the idea to minimize the travel time needed to pick an order. Accorsi et al. (2012) summarize the most used heuristics for the storage assignment strategies. We add the order oriented slotting (OOS) heuristic of Mantel, Schuur, and Heragu (2007) to their list:

- **Class-based storage rule**
  ABC analysis, see Section 3.2.

- **Ranked index-based rules**
  - *Popularity*
    SKUs are sorted on popularity and the most popular SKU is stored in the location closest to the I/O point.
  - *Cube per order index (COI)*
    The idea of COI is to put the SKU with the lowest COI index in the most favorable location (Heskett, 1963).
    $$COI = \frac{\#\, required\ storage\ locations}{\#\, trips\ in/out\ of\ storage\ per\ period}$$
- **Correlated storage assignment policy**
  - *Order oriented slotting (OOS)*
    With OOS, order picking is considered during the design of the slotting. The idea of OOS is to design the slotting in such a way the total travel distance of all orders is minimized (Mantel et al., 2007).

Schuur (2015) proves that in the worst-case scenario the broad adopted COI may perform infinitely bad compared to OOS.

For combined storage there are also multiple strategies possible. Tang and Vasili (2012) find the following strategies:

- **Randomized storage**
  Items are stored in a random location.
- **Closest open location (COL)**
  Items are stored in the closest open location from the current position.

Jansman (2014) compares storage strategies for a VLM. He compares combined storage, dedicated storage, and dedicated storage with sequence optimization. The criteria he uses are: probability of human errors, in/out put speed, flexibility, and space utilization. He states combined storage is the best option for a VLM. A way of designing a combined storage slotting for a VLM is by using bins of different sizes (Jansman, 2014). Materials are assigned to a bin corresponding to their size, the WMS then assigns the bin to a location with an empty bin of the same size. This storage strategy makes it possible to store multiple units of a material in different trays.

The slotting can be designed to optimize the put away process, or to optimize the picking process. The picking process determines the output of the warehouse, and typically accounts for 55% of the costs of the warehouse. Therefore, most Warehouses use a slotting that optimizes the picking process (Manzini, Bindi, Ferrari, & Pareschi, 2012).

3.3.2 Picking

The picking process is the most important process in the warehouse. The picking process consist of three stages:

- Travel to the zone of the SKU needed.
- Localize the SKU needed in the zone.
- Pick the SKU.

From the picking activities, only the actual picking of the material is a value-added activity, the other activities are just waste. The goal is to minimize the waste for every order. The easiest way of picking a material is by a single command cycle, travel from the origin to the picking location, pick the material, and travel back. This procedure has a lot of non-value-added movements, that is why a dual command cycle performs better. In a dual command cycle both the storage and retrieval are conducted during one cycle (Manzini et al., 2012). Depending on the number of picking lines per order, it can be beneficial to batch multiple orders. If order lines are batched, the materials need to be sorted. There are two ways of dealing with the sorting of picked materials; sort-while-picking and sort-after-picking (Park, 2012). The picking lines should be sorted in a such a way that the total travel distance is minimized.

3.4 Conclusion

This chapter provides the theoretical framework for the research. The activities in the flow of goods can be grouped in receiving, putting away, storage, picking, and delivering. Staudt et al. (2015) provide a list of performance indicators to use for the performance measurement of these activities. The performance is measured in four dimensions: time, cost, productivity, and quality. The flexibility is not directly measurable. It is important performance indicators do not create unwanted behavior (Caplice & Sheffi, 1994).

Section 3.2 discusses different replenishment strategies. There are different strategies possible to determine the order quantity, and the point in time to place the order. It is common to use different strategies for different group of materials. Materials can be grouped based on the Pareto Principle, or in case of multiple criteria inventory classification, with AHP. The arrival process in the warehouse depends on the used replenishment strategy.

There are two storage strategies: dedicated storage, and combined storage. Each option has it pros and cons. The detailed design of the storage locations and the assigned 'stock keeping units' is called the slotting. The design of the slotting is important for the travel times in the warehouse.

If the picking process is considered during the design of the slotting it is possible to minimize the total travel distance of all orders. This is called Order Oriented Slotting, developed by (Mantel et al., 2007). In the picking process, dual command cycles perform better than single command cycles. Batching picking lines reduces the total time needed for the picking activity. With the batching of order lines, materials can be sorted during, or after the picking procedure.

Figure 3-1 gives an overview of the studied theories and how they contribute to this research. Chapter 4 uses these theories for the design of different experiments.

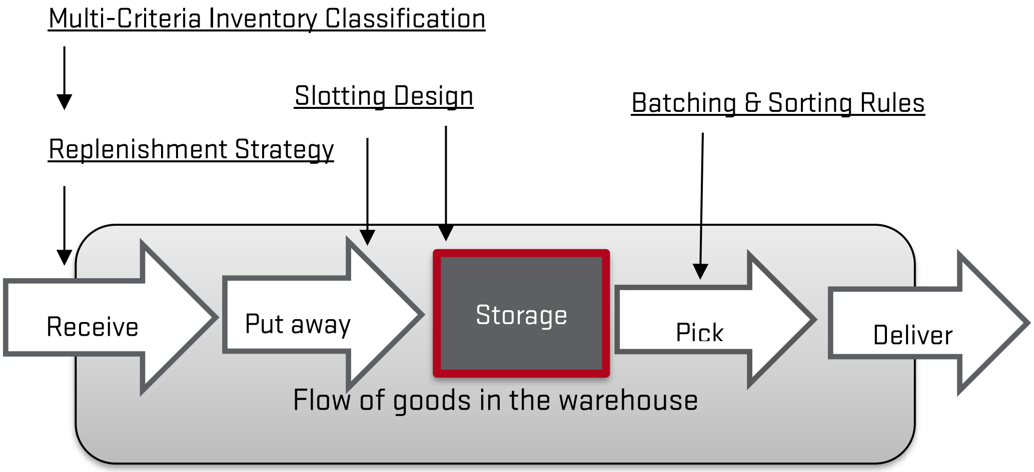


Figure 3-1 Overview of the literature study and how it is used in this research.

4 Solution Design

From Chapter 3 we know suitable performance indicators to measure the performance. Chapter 3 also provided potential replenishment, and warehouse strategies for VSM. In Chapter 4 we use this information to answer Question 3 '*What is the current performance and how can it be improved?*'. First, Section 4.1 identifies the stakeholders for this research. The stakeholders contribute to the selection of KPIs, introduced in Section 4.2. Sections 4.3, 4.4, and 4.5 use the findings of Chapter 3 to suggest possible improvements for the replenishment, storage, and picking strategies. These strategies are used to define several experiments in Section 4.6. Finally, Section 4.7 concludes this chapter.

4.1 Stakeholders

The performance measurement should not create a conflict of interest between different departments. Therefore, we identify the stakeholders for this research. The broadly adopted definition of a stakeholder is 'any group or individual who can affect, or is affected by the achievement of the organization's objectives' (Freeman, 2010). Based on this definition we define the stakeholders involved in the flow of goods described in Section 2.2. Mitchell et al. (1997) introduce a framework in which stakeholders can be placed. This framework consists of three attributes a stakeholder could have. These attributes are:

- **Power**
  A stakeholder, say A, has power when it can get another actor, say B, to do something that B would not have done otherwise.
- **Urgency**
  Urgency is the degree to which the stakeholder claim calls for immediate attention. This is based on time: - the degree to which managerial delay in attending the claim is unacceptable to a stakeholder, and on criticality: - the importance of a claim to the stakeholder.
- **Legitimacy**
  A stakeholder has legitimacy when the actions of the actor are within a generalized perception of a socially constructed system of norms, values, and beliefs.

The framework provides eight different combinations with zero, one, two, or three attributes possible. We identify the following stakeholders for this research:

- **Board**
  The Board is responsible for a positive business result. A change in the current way of working will have influence on this result. With the power to act but with no urgency and legitimacy the Board is a *dormant* stakeholder.
- **Data Management**
  The Data Management Department must make sure all the necessary communication between the departments runs without errors. If the procurement of buy parts will be based on inventory levels, the ERP system should be designed accordingly. This means the right settings in the ERP system should be applied. Data Management possesses no power to other stakeholders and lacks urgency. This makes them a *discretionary* stakeholder.

- **Planning**
  The time needed to gather all the materials needed for an order is important to take in to account when the orders are scheduled. A possible change in this internal lead time can have consequences for the planning. The planning department has no power and urgency for a possible transition to working with anonymous inventory instead of the current order reserved inventory. Planning is also considered a *discretionary* stakeholder.
- **Production**
  The production department is dependent on the output of the warehouse. Without a supply of materials from the warehouse the production department cannot assemble the machines. Production benefits from a good performance in the warehouse. In the current situation, there is no urgency for the production department. Production also does not possess power towards the other stakeholders making it a *discretionary* stakeholder just as Planning and Data Management.
- **Purchasing**
  It is important to realize a stable and short lead time for the needed materials. The way of procurement is a result of the used inventory policy, and different policies require different relations with the suppliers. The purchasing department possesses some power towards the warehousing department, and Data Management. Urgency is lacking for the purchasing department making them a *dominant* stakeholder.

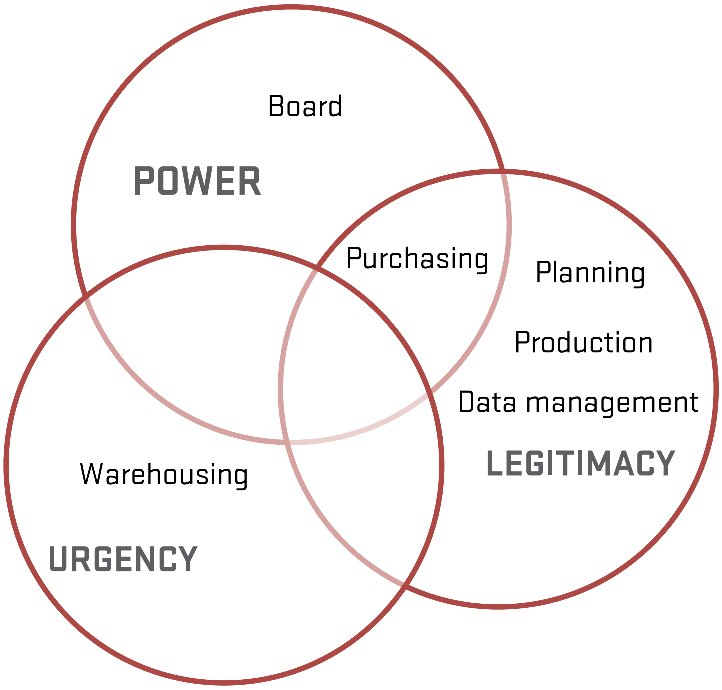


Figure 4-1 The stakeholder map from Mitchell, Agle, and Wood (1997) adapted to the Voortman case.

- **Warehousing**
  The physical flow of goods completely takes place at the Warehousing Department. A change in the inventory strategy requires a different way of handling incoming goods. This affects the responsibility of the warehousing department to make sure every production order can start at the scheduled time with all the needed materials. Warehousing has the urgency for a change, as the current way of working requires more time than desired. Therefore, Warehousing is considered a *demanding* stakeholder.

Figure 4-1 shows the stakeholders in the framework of Mitchell et al. (1997). For the original framework, and all eight types of stakeholders, see Appendix C.

4.2 Key Performance Indicators

To find out the consequences of new strategies for the replenishment and storage of buy parts performance measured is needed. In the current situation, VSM monitors the value of the materials present in the warehouse. The time to process incoming goods is another performance indicator VSM uses. Incoming goods need to be processed within one day after arrival. This is not monitored real time, but on a trust base. If there are no complaints from other departments, no measures are taken to improve this processing time. Another indicator in place is the time needed to deliver a production request to the work floor. By communicating the current workload between the Production Department and the Warehouse Department, potential delays are prevented. The delivery time is not measured.

There are other performance indicators used for the activities in the flow of goods. We summarize the different activities in the flow of goods:

- **Receiving**
  Suppliers deliver the materials by a truck or by a delivery van. The materials are unloaded and randomly subjected to a quality check.
- **Put away**
  Put away is the procedure of storing the received materials in the Warehouse. The storage could be in the AS/RS, in the VLM, or on the floor for the big and lumpy materials.
- **Storage**
  The storage itself is not really an activity that requires action. Storage can also be seen as inventory, and that is considered a key to achieve excellent service (Gallmann & Belvedere, 2011).
- **Picking**
  Picking is the gathering of the different materials needed for a production order.
- **Delivery**
  At VSM the delivery activity is the output of the Warehouse, and the input for the Production Department. The collected materials for a production order leave the warehouse in a project pallet, and these project pallets are transported to the work floor.

Figure 4-2 gives a graphical representation of these activities.

Figure 4-2 The different activities in the flow of goods in the warehouse.

The overview of performance indicators for warehouse activities in Table 3-1 is suitable for a MTO environment. We adapt the overview to make it suitable for the ATO_{ED}, MTO_{PD} environment of VSM. Table 4-1 shows the result of the adaption. The pink shaded fields are indicators currently in place at VSM. An indicator VSM is curious about, but that is not monitored, is the time spent by a material in the warehouse, also known as the duration of stay (DOS). None of the articles Staudt et al. (2015) review use an indicator for the DOS of a material in the warehouse, but with a simulation model it is possible to measure the DOS of an individual material in the warehouse. The other activity specific indicators in the time dimensions indicate the needed time per activity per day in minutes. The order lead time is a process transversal indicator, indicating the total time the departments spend on all tasks relating to an order. This is difficult to measure as not all tasks are dedicated to one order, therefore this indicator is not considered as a KPI.

Table 4-1 Performance indicators per dimension, adapted to the Voortman case from Staudt et al. (2015).

	Dimensions	Time	Quality	Cost	Productivity
Activity - specific indicators	Receiving	Receiving time			
	Storage	Put away time			
	Inventory	Duration of stay	Physical inventory accuracy	Inventory cost	Inventory space utilization
	Picking	Order picking time	Picking accuracy		Picking productivity
	Delivery	Delivery time			
Process Transversal indicators	Inbound Processes		High priority ratio		Throughput
	Outbound Processes	Order lead time	Perfect orders	Order processing cost	Throughput
Resource related indicators	Labor			Labor cost	Labor productivity
	Equipment and building				Warehouse utilization

The physical inventory accuracy indicates the difference between the documented inventory and the actual inventory by location and units. The picking accuracy indicates the number of errors in the picking process per project.

The high priority ratio indicates the number of high priority order lines per total number of purchase order lines per project. The indicator 'perfect orders' indicates the percentage of orders delivered to the Production without missing materials or high priority orders.

The ERP system currently measures the value of inventory. This indicates the total monetary value of the materials present in the warehouse. The order processing cost indicates the total cost for processing all purchasing orders per project. These costs are hard to measure as they consist of many different, and shared activities. The labor cost indicates the cost for the total labor amount of labor needed per project.

The first indicator in the productivity dimension is the inventory space utilization. This indicator indicates the required amount of space needed to store all materials, measured as a percentage of the available space in the warehouse. The picking productivity indicates the number of picks per labor hour. The inbound throughput indicates the number of materials received and put away per hour. The outbound throughput indicates the number of materials picked and delivered per hour. The labor productivity indicates the ratio of the total number of store/pick activities per labor hour. The warehouse utilization indicates the average amount of warehouse capacity used over a specific amount of time. Without considering all materials it is not convenient to measure the warehouse utilization in this research.

As mentioned in Section 3.1, it is not possible to measure the flexibility directly. Section 2.4 describes some processes relating to the flexibility at VSM. We identify indicators based on these processes, resulting in Table 4-2. The production order productivity consists of two indicators: the purchasing productivity, this is the number of purchasing lines needed per order, and the rework rate, this is the amount of rework needed per project. The backorder rate is the number of backorders per project. A backorder occurs if a part breaks during assembly, or if a part arrives too late. The material retour rate indicates the number of left over materials going back to storage after finishing the assembly per project. The error rate in the column 'Quality' indicates the number of errors in the installed base per project. The material retour rate, and the number of errors in the installed base are currently not measured. The lead time for the Production is the time the Production must wait for the supply of materials from the warehouse. The material availability indicates the amount of missing materials from a production order at the beginning of the assembly. For an overview of the detailed descriptions of all the indicators in Tables 4-1 & 4-2, see Appendix D.

Table 4-2 The performance indicators for flexibility related processes.

	Dimensions			
Activities	**Time**	**Cost**	**Productivity**	**Quality**
Production order			Purchasing productivity; Rework rate	Backorder rate
Retour process				Material retour rate
Installed base				Error rate
Production	Lead time			Material availability

Not all indicators from Tables 4-1 & 4-2 are useable for this research. For example, the number of high priority purchase requests is not monitored. Therefore, it is not possible to determine ratio of high priority purchase requests. The inventory space utilization is an indicator not worth to measure in this research, because only a selection of all materials is considered. Also, the performance indicators need to be measurable in the simulation model.

Taking these restrictions in mind, and in consultation with the stakeholders, we select the key performance indicators to use for this research. Table 4-3 lists the selected key performance indicators.

Table 4-3 The key performance indicators for this research.

Indicator	Description	Dimension
Inventory cost	Average cost of the materials in the warehouse	Cost
Inventory time	Total time an item spent in the warehouse until assembly	Time
Labor productivity	Number of warehouse actions needed per material	Productivity
Labor time	Number of FTE of personnel involved in warehouse operations	Time/Cost
Receiving time	Time needed to unload and prepare all incoming materials	Time
Put away time	Time needed to store all incoming materials in the warehouse	Time
Order picking time	Time needed to collect all the materials for a production request	Time
Warehouse productivity	Number of store/pick cycles per storage location (AS/RS, VLM)	Productivity
Throughput	Number of items/orders per day that leave the warehouse	Productivity

4.3 Replenishment

The performance indicators in Table 4-3 all depend on the inbound flow in the warehouse. The used replenishment strategy determines the size and timing of the inbound flow. As not all the materials have the same characteristics, we perform a multi-criteria inventory classification to group the buy parts. The criteria used are: the demand, defined as the number of requests for a material in a year, and inventory cost, defined as the price per piece. We assume the lead time of a buy part is always less than 4 weeks, and therefore not relevant for the classification. The demand per year is important, because if there are for example only 5 requests for a material in a year, there is a risk the material becomes obsolete before the inventory is used. Inventory cost is important for the business result, as every material in stock must be financed in advance. The buy parts are classified in three groups per criteria. We do not use the Pareto principle discussed in Section 3.2.2, but absolute rules, as we do not consider all buy parts.

Table 4-4 Characteristics of the materials in the different groups.

Criteria	Group A	Group B	Group C	Group X
Demand: no. of requests per year	12 or less	Between 12 and 52	52 or more	0
Inventory cost: price per piece	€500 or more	Between €50 and €500	€50 or less	-

Based on the inbound flow of the buy parts from 2nd of January until 31st of May, we determine the demand for the buy parts in the selection of 373 materials, identified in Section 2.1. Apart from the three groups, A, B, and C, we add a group X. The materials in this group have a demand of zero over the past five months. These materials are not part of the flow of goods in the warehouse. The cause of this zero-demand is not examined, as it does not contribute to the objective of this research.

Materials with a low demand, we say less than 12 requests per year, are Group A. The Group C materials have a high demand, we say more than 52 requests per year. The remainder of the materials is assigned to Group B.

The ERP system provides the price per piece. Materials with a high price per piece, we say €500 or more, are Group A materials. The cheap materials, with a price per piece of €50 or less, are Group C materials. The remainder of the materials, with a price per piece between €50 and €500, are Group B. Table 4-4 summarizes the characteristics of the groups per criteria.

Table 4-5 Matrix used for the ABC classification of the buy parts.

		Demand			
		A	B	C	X
Inventory cost	A	A	A	B	X
	B	A	B	C	X
	C	B	C	C	X

We use both criteria to form the classification. The matrix in Table 4-5 shows how the two criteria together form the classification. For example, a material with a demand of 60 requests per year, and a cost per piece of €1000, is classified in Group B.

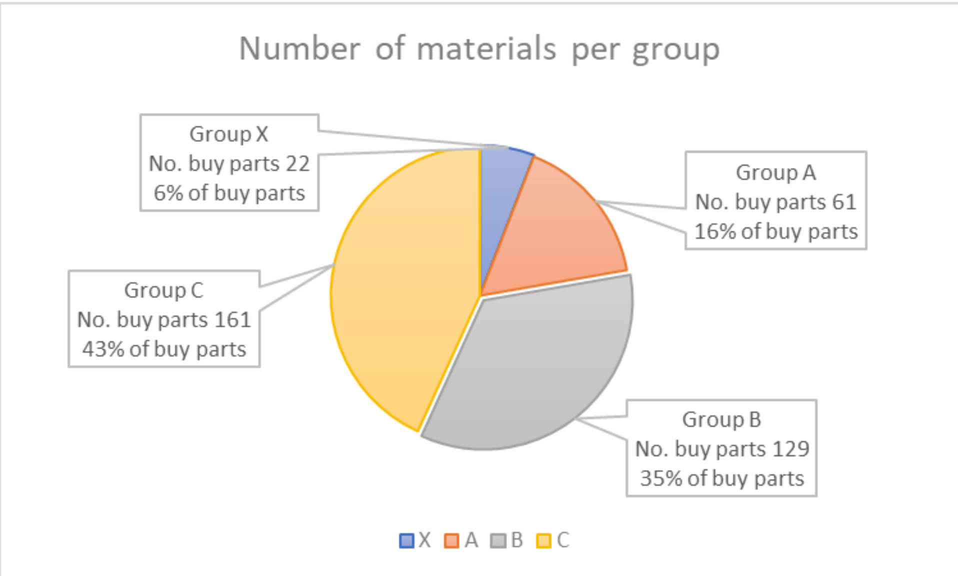


Figure 4-3 The buy parts classified in different groups.

Figure 4-3 gives an overview of the number of materials per group. Table 4-6 gives the average characteristics of the buy parts per group. Interesting is the average price per material, and the average price per order of a material. This is more than hundred times higher for group A than for group C. The number of delivery days per material is also remarkable. The materials in group C, the high demand and cheap materials, are delivered on average 13.3 times over these five months. This indicates the number of actions in the warehouse can be reduced if the purchase orders for group C materials are bundled, and delivered for example once every two weeks.

Table 4-6 Analysis of the arrival of the buy parts over the January – May 2017, categorized in groups.

Group	A	B	C	X
Number of materials	61	129	161	22
Average no. of delivery days per material	6.7	7.5	13.3	-
Average price per material	€ 2,213	€ 114	€ 14	-
Average value per purchase order	€ 7,679	€ 331	€ 44	-

We analyze all the deliveries of the buy parts by identifying the different suppliers. In total 38 different suppliers have delivered one or more relevant buy parts between the 2nd of January and the 31st of May. A result of the current used lot-for-lot strategy is a high number of orders with small order quantities. The 38 suppliers made a total of 690 deliveries in this period. Table 4-7 gives an overview of facts about the deliveries. If each supplier had visited VSM at most once a week, just 422 deliveries would have been made. This is a saving of 268 deliveries, on average 10 deliveries per week less.

Table 4-7 Statistics of the suppliers and deliveries over January – May 2017.

Criteria	Quantity
Total number of suppliers	38
Total number of deliveries	690
Average number of deliveries per week	31.36
Total number of deliveries if at most once a week	422
Average number of deliveries per week if at most once a week	19.18

Based on the findings of Section 3.2 we propose a different replenishment strategy than the current used lot-for-lot strategy, for the materials in Groups B and C. For the materials in Group B we suggest a FOP strategy. With a FOP strategy, the number of orders per week for a material is limited to one. The suggested strategy for the materials in Group C is a EOQ strategy[1]. The order quantity is determined with Camp's Formula, based on the average demand for the material per year. If the inventory level drops below a safety stock level s, a new order is placed.

[1] To reduce complexity of the simulation model, and due to a lack of data to use the EOQ formula we choose to use a FOP strategy for group C materials in Section 4.6.

Using a fixed order quantity is good for the supply chain, because suppliers can adjust their processes to the order quantity demanded by VSM. Table 4-8 gives an overview of the replenishment strategy per group. We refer to this replenishment strategy with 'ABC replenishment' in Section 4.6.

Table 4-8 Characteristics of suggested replenishment strategy per group of buy parts.

	Group A	Group B	Group C
Review period	Continuously	1 week	Continuously
Delivery frequency	When needed	Once every 1 week	When inventory level is below reorder point *s*
Order size	Lot-for-lot	Aggregated demand	EOQ
Strategy	Lot-for-lot	FOP	EOQ

4.4 Storage

The suggested replenishment strategy influences the activities in the warehouse. The arrival process changes with a different replenishment strategy than the current used lot-for-lot strategy. The activities receiving and delivery cannot be changed to a more efficient strategy without changing the physical warehouse. The put away, storage, and picking activities can be influenced to increase the efficiency or flexibility. The design of the storage locations influences all these three activities.

As mentioned in Section 2.2, VSM has three different storage locations to store the buy parts. On the floor, in a pallet in the AS/RS, or in a tray in a VLM. Depending on the measures and weight of the parts not all locations are suited for every material. Big and heavy parts do not fit in the AS/RS or VLM, and small parts get lost when they are stored on the floor.

4.4.1 Floor

The scope of this research does not include materials that are stored on the floor. The materials stored in this location cover only a small part of the total flow of goods, and are therefore not relevant. The current strategy used best described as Closed Open Location (COL). The time spent on storing, and picking materials in this location is not known, but we assume improvements are possible. In the recommendations for future research in Section 7.4, we propose a different storage strategy for this storage location.

4.4.2 AS/RS

As mentioned in Section 2.3, a Warehouse Management System (WMS) controls the AS/RS. It is the software that decides the storage locations of the Stock Keeping Units (SKU). The pros of dedicated storage, see Table 3-3 on page 23, are not in place for the AS/RS. The order picker gets the pallets presented in the I/O point, so the actual searching is not needed. The big disadvantage of the AS/RS is the space utilization, as the available capacity is limited. The WMS currently uses a COL strategy. A change in storage strategy requires a change in the software, but VSM does not own this software. Based on the results of Table 3-3 we agree with the current COL strategy for the project pallets.

For the few pallets that are used for inventory of materials, we propose a combination of class based storage and Order Oriented Slotting (OOS). Materials that are frequently picked together, and have dimensions that allow multiple SKUs in a pallet should be assigned to the same pallet. This will minimize the number of store/pick cycles during the picking process.

4.4.3 VLM

Just as the AS/RS, the VLM is controlled by a WMS, and it uses the COL strategy for the trays. As mentioned in Section 2.2.2 the trays of the VLM are used for spare parts and for bulk items. Those materials are not part of this research, but we still review the used storage strategy and the operating speed for future use. Every tray has a different fixed layout, a dedicated storage strategy. The warehouse chef manually configures the layout of every tray, based on a mixture of class based storage, OOS, and a lot of experience. Class based storage is used to prevent unnecessary empty space between trays. By putting items of the same dimension in a tray the height profile per tray is uniform, and no space is wasted in the VLM.

In case of anonymous storage for buy parts, a VLM can be used. We suggest a combined storage strategy for trays. Using the OOS principle, materials are assigned to a group based on the frequency of joined projects. For example, if material A has a lot of orders in common with material B, these materials are assigned to the same group. A disadvantage of combined storage, a longer put away time, can be compensated with a faster picking process.

4.5 Picking

The current picking process is combined with the put away activity, because of the project based storage. This combination reduces the waste in the picking process, as materials are stored directly in a project pallet, see Figure 4-4. The project based storage at VSM, is not possible when using a Fixed Order Quantity (FOQ). With anonymous storage, the picking process is separated from the put away activity. We now describe how the picking process at VSM should be designed in case of anonymous storage.

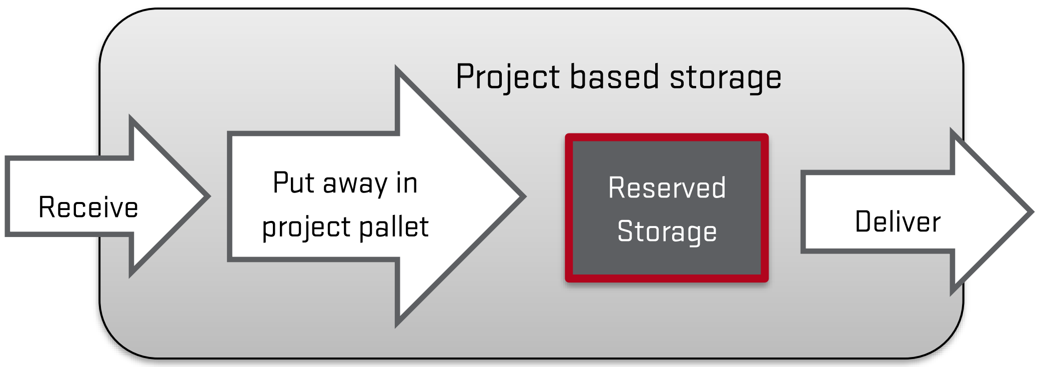


Figure 4-4 The flow of goods with project based storage.

Compared to the current project based storage, anonymous storage requires two additional physical movements per material. Figure 4-5 shows these additional movement with the pink arrows. The materials are picked from storage and then put away in a project pallet. If all materials of a project are stored at the same time, then only one store/pick cycle per pallet is needed. This can lead to a shorter time needed per order.

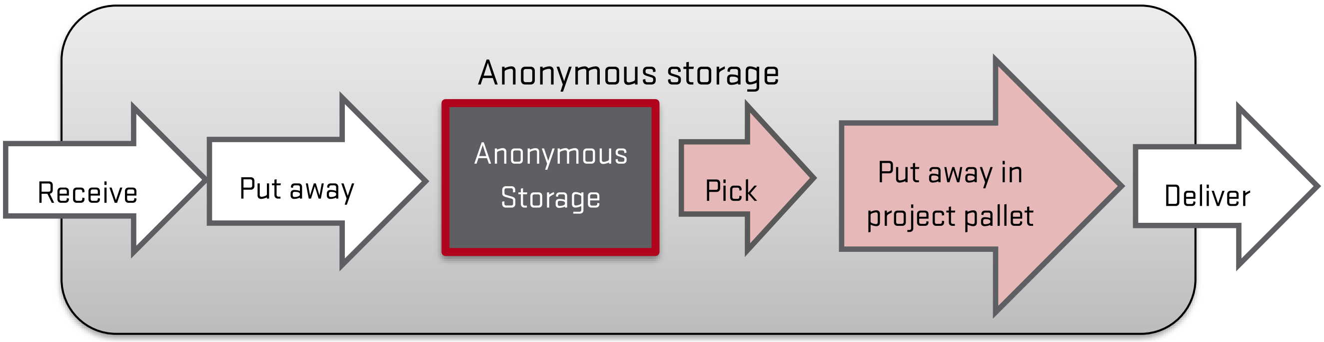


Figure 4-5 The flow of goods with anonymous storage.

Both storage locations, the AS/RS and the VLM, can be used for the storage of buy parts with anonymous storage. The picking process is quite similar for the AS/RS and for the VLM as Table 4-9 shows. The AS/RS and VLM, automatically store and retrieve the pallets or trays. The pallet or tray is transported to the pick location by the crane, or by the lift. And both the crane and the lift use dual command cycles, reducing the empty travel distance by the crane or lift.

Table 4-9 Order picking activities per storage area.

Picking activity	AS/RS	VLM
Travel to zone	Walk to the I/O point of the AS/RS (manual)	Walk to the I/O point of the VLM (manual)
Localize the SKU	Retrieval of the pallet (automated)	Retrieval of the tray (automated)
Pick the SKU	Grab the SKU (manual)	Grab the SKU (manual, pick-to-light)

Section 1.2 mentions the prevailing idea at VSM, that anonymous stock for the buy parts could help to increase the flexibility. This idea exists because the AS/RS requires a lot of time for a store/pick cycle. Especially compared to the time a VLM needs to perform a store/pick cycle. We perform a time study for both the AS/RS, and the VLM, to measure the time needed for a store/pick cycle.

4.5.1 AS/RS

Table 4-10 shows the movements that a pallet makes during a store/pick cycle. The descriptions of the movements are based on the naming used in Figure 2-6. To perform a store or pick activity for a material in the AS/RS, the crane retrieves a pallet from its storage location, and transports it to the beginning of the conveyor belt.

The conveyor belts transport the pallet to the pick location. After finishing the store or pick activity, the pallet is transported to the end of the conveyor belt. There, the crane retrieves the pallet from the conveyor belt, and puts it back in storage.

We measure the time needed for each movement by hand. To reduce measurement errors, we measure each movement thirty times. Table 4-10 shows the average measured time per movement, and the standard deviation of the average measured time per movement.

The question marks in Table 4-10 indicate that time needed for the movement is not known. The travel distance along the straight part of the aisle depends on the storage location. Therefore, the time needed for these movements in a store/pick cycle is unknown. The time needed for the store/pick activity is also not known. This time depends on the number of materials in the store/pick activity, and on the dimensions of those materials.

We assume the crane travels on average once through the corner during a store/pick cycle. On average, a store/pick cycle in the AS/RS takes then at least 161 seconds. The travel time across the straight part of the track, and the store/pick time, are not included in the average time per store/pick cycle. A pallet spends a relatively long time on the conveyor belts during the store/pick cycle. The conveyor belts act as a buffer for the crane, so the crane does not have to wait for a new mission. The conveyor belts can carry up to 10 pallets at the same time. The crane can only carry one pallet at once.

The minimum time a pallet spends on the conveyor belts during a store/pick cycle is 85.7 seconds. The store/pick activity is not included within this 85.7 seconds. Without the travel time across the straight part of the track, the total average crane time per store/pick cycle is 75.2 seconds. If we assume that the unknown crane travel time on the straight part of the track is 10 seconds and that the store/pick time is zero, the system is steady. That is, the crane time is then the same as the 'buffer' time. We define this situation as the best-case scenario.

Table 4-10 The different movements and duration in seconds of a pallet in a store/pick cycle.

Movement	Average time (s)	Standard deviation (s)
Retrieval	12.6	0.75
Move to OUT station (depends on travel distance)	?	?
Storage on outfeed conveyor	12.1	1.02
Conveyor A-B-C	26.2	0.50
Conveyor C-D-E	18.9	0.53
Store/Pick activity	?	?
Conveyor E-F-G	17.2	0.58
Conveyor G-H-K	23.1	1.20
Retrieval from IN station	12.6	0.75
Travel in Crane through the corner	25.7	2.33
Move to storage location (depends on location first open slot)	?	?
Storage	12.1	1.02
Total	160.5	2.63

With the formula, better known as Little's Law (2), we calculate the average pallet throughput (TH) of the AS/RS system in the best-case scenario. The throughput is the number of pallets per hour that undergo a store/pick cycle.

$$WIP = CT \times TH \tag{2}$$

We assume the crane is constantly busy and that it takes no time store/retrieve a pallet. The Work-In-Progress (WIP) of the crane is then 1. The Cycle Time (CT) of the crane is 85,7 seconds. By adjusting Little's Law (2) to (3), we come to a throughput of 42 pallets per hour in the best case.

$$TH = WIP/CT = \ 3600/85.7 = 42.0 \tag{3}$$

In practice the throughput is less than 42 pallets per hour, due to longer travel distances for the crane and, because the time needed for the store/pick activities is greater than zero. The throughput is even less when there is a production request and some project pallets are transported to the I/O station.

4.5.2 VLM

The store/pick cycle for the VLM is less complex than the store/pick cycle from the AS/RS. Table 4-11 shows the movements of a tray in a store/pick cycle. In the description of the movements we refer to the naming of the arrows in Figure 2-8 on page 15. The lift retrieves a tray from it storage location, and transports the tray down to the I/O point. At the I/O point the store/pick activity takes place. After finishing the store/pick activity, the lift takes the tray back in, and transports it to the closest open location.

We measure the time needed for each movement by hand. To reduce measurement errors every movement is measured thirty times. Table 4-11 shows the average measured times, and the standard deviation, per movement.

Table 4-11 The different movements and durations of a tray during a store/pick cycle in seconds.

Movement	Average time (s)	Standard deviation (s)
Retrieval (r/s)	5.7	0.52
Move to I/O point (depends on travel height Y)	?	?
Take tray out (X)	8.3	0.37
Store/pick activity	?	?
Take tray in (X)	7.7	0.32
Move to closest available slot (depends on travel height Y)	?	?
Store (r/s)	5.1	0.47
Total	26.8	0.85

The vertical travel distance in the lift column depends on the storage location of the tray. Therefore, the time needed for these movements in a store/pick cycle is unknown, and indicated with a question mark in Table 4-11. The time needed for the store/pick activity is also not known. This time depends on the number of materials in the store/pick activity, and on the dimensions of those materials. The total time needed for a store/pick cycle of a tray in a VLM is at least 26.8 seconds. The travel time in the lift in vertical direction is not included in these 26.8 seconds. The I/O point of the VLM can hold 2 trays at the same time, acting as a small buffer for the lift. The lift can hold only 1 tray. We define a best-case scenario in which the travel time in vertical distance is 2 seconds.

A store/pick cycle takes then 30.8 seconds, this is without the time for the store/pick activity. Just as with the best-case scenario for the AS/RS we assume the WIP of the VLM is 1. For this best-case scenario, we calculate the average tray throughput with (4), and come to a throughput of 117 trays per hour. So, a VLM can perform at most 117 store/pick cycles per hour in the best case.

$$TH = WIP/CT = 3600/30.8 = 116.8 \tag{4}$$

4.5.3 Comparison AS/RS and VLM

Both storage systems, the AS/RS and the VLM, are basically the same in the way they operate. There is a transporter, a crane in the AS/RS, and a lift in the VLM. The transporters both transport a storage unit from a storage location to a pick location and vice versa. In the AS/RS the storage unit is a pallet, and in the VLM the storage unit is a tray. Both systems are closed and have a fixed maximum capacity. In the AS/RS the number of pallets in use can vary, where the number of trays in a VLM is constant. Because the size of the 'buffer' is different for the AS/RS and the VLM, 8 and 1, comparing the TH of both systems is not possible. Table 4-12 summarizes the comparison of both storage systems. Based on the time measurement and the experience VSM has with both systems we define the AS/RS as the bottleneck in the put away and pick activities.

The time needed per order in the warehouse depends on the number of store/pick cycles needed. Because the materials for a project arrive at different points in time, a project pallet can undergo multiple store/pick cycles before either the pallet is full, or the project is complete. Unfortunately, there is no data present that specifies the number of store/pick cycles per project pallet before the project pallet is transported to the work floor.

Table 4-12 Comparison of the AS/RS and VLM.

	AS/RS	VLM
Transporter	Crane	Lift
Storage unit	Pallet	Tray
Storage unit dimensions	1200 x 800 x 400 mm	3000 x 8000 mm
Storage capacity	1337 pallets (± 1050 used)	60 trays
Transporter buffer size	10 pallets	1 tray
Average number of store/pick cycles in the best case	42 pallets per hour	117 trays per hour
Minimal CT	161 seconds	27 seconds
Pros	Pallets can be transported to the work floor	Fast store/pick cycle; Small space occupation
Cons	Slow store/pick cycle	Trays cannot be taken to the work floor

Based on the comparison of the AS/RS and the VLM, we suggest using the VLM for anonymous storage. The production requests from the Production Department require multiple materials, leading to multiple picking lines per project. We suggest batching the lines per project, in this way materials needed for a project are stored at the same time, reducing the number of store/pick cycles needed to fill the project pallets.

4.6 Scenarios

We now have a set of KPIs for the performance measurement, a new replenishment strategy, and a warehouse strategy for anonymous storage. With this information, we define multiple experiments. The objective of this research is to get to know the consequences of a new replenishment strategy, and of anonymous storage for the buy parts. Both aspects of the objective, a new replenishment strategy, and anonymous storage, are variables in the different experiments. We formulate the experiments as different scenarios for VSM. Per scenario we make one or more interventions. In Chapter 5 we introduce the simulation model we use for the experiments.

4.6.1 Scenario 1: Project based storage with historical arrival

Scenario 1 is a representation of the current situation. The current flow of goods is unchanged, incoming materials are stored directly in a project pallet. In this scenario, the arrival process of the buy parts is equal to the historical data. The AS/RS contains only project pallets, and the VLM is not used. With this experiment, we determine the performance of the current situation at VSM.

Intervention 1.1 One arrival day per order

Intervention 1.1 has the goal to reduce the number of pallet retrievals per project. With this intervention suppliers deliver all the materials needed for a project on one day. All deliveries for a project take place on the same day. In this way, all materials of a project arrive at the same day, reducing the number of pallet retrievals per project. This arrival process requires a lot of planning and communication with the suppliers, and is not realistic for VSM. But it is interesting to see the influence of a reduction in pallet retrievals per project on the performance.

Intervention 1.2 Fixed delivery day

Intervention 1.2 has the goal to reduce the number of deliveries per day. In this intervention suppliers visit VSM at most once a week, on their preferred delivery day. The idea is that less deliveries reduces the time needed for the unloading and unpacking activities.

4.6.2 Scenario 2: Anonymous storage with historical arrival

In Scenario 2 the arrival process is the same as in Scenario 1, corresponding to the historical data. The flow of goods is changed to anonymous storage. Incoming goods are first stored in the VLM. A day before the production request of an order, the materials needed are picked from the VLM and stored in a project pallet in the AS/RS. The flexibility increases as materials are 'free to use'. Section 2.4 discusses processes relating to the flexibility at VSM. For example, the installed base becomes more accurate with anonymous storage, as single materials are linked to a project when they are picked. The return process becomes less complicated, and exchange procedures in case of shifted deadlines are no longer needed.

Intervention 2.1 OOS tray slotting

Intervention 2.1 has the goal to reduce the time needed for the picking process. By reducing the number of tray retrievals needed for a pick request, the picking time per project decreases. In this intervention materials are assigned to a group, based on the frequency of joined projects. For example, if material A has a lot of orders in common with material B, these materials are assigned to the same group. There are seven groups. The trays in the VLM are assigned to one of the seven groups. Only materials from the same group as the group assigned to the tray, may be stored in that tray. If a tray reaches its maximum capacity, an empty tray is assigned to the same group.

4.6.3 Scenario 3: Anonymous storage with ABC Policy

In Scenario 3 the storage is also anonymous. The difference with Scenario 2 is the arrival process. Scenario 3 uses the ABC replenishment from Section 4.3. The materials of group A are ordered with a lot-for-lot strategy. Group B materials are ordered with a fixed-order-period of one week, and group C materials are ordered with a fixed-order-period of four weeks. The strategy for group C does not correspond with the strategy suggested in Table 4-8. To reduce the complexity of the model, and because too much information is lacking to use the EOQ formula, we use FOP instead of EOQ. This 'ABC replenishment' strategy reduces not only the number of deliveries, but also the number of purchase orders per material.

Intervention 3.1 OOS tray slotting

This intervention is the same as Intervention 2.1. It has the goal to reduce the time needed for the picking process. The materials are grouped the same as in Intervention 2.1, based on the frequency of joined projects.

4.7 Conclusion

The stakeholders for this research are the following departments: the board, data management, planning, purchasing, production, and warehousing. Together with the stakeholders and the performance indicators from the literature we drafted a set of KPIs. With a multi-criteria inventory analysis, we divide the materials in four groups. The lot-for-lot replenishment strategy is suited for the materials in group A. For the materials in group B we suggest using FOP as replenishment strategy. The suggested replenishment strategy for the materials in group C is EOQ. Group X consists of obsolete materials.

We designed the warehouse strategy for anonymous storage. Based on a time study we suggest using the VLM for anonymous storage of materials. To measure the performance of the new strategies we defined several experiments in Section 4.6. Table 4-13 gives an overview of the experiments. Next, Chapter 5 introduces the simulation model to use for the experiments.

Table 4-13 Summary of the different scenarios and interventions.

Experiment	Replenishment strategy	Storage strategy	VLM design
Scenario 1	Lot-for-lot: Historical data	Project based	Not used
Intervention 1.1	All materials for a project arrive on the same day	Project based	Not used
Intervention 1.2	Fixed delivery day per supplier	Project based	Not used
Scenario 2	Lot-for-lot: Historical data	Anonymous	First-fit
Intervention 2.1	Lot-for-lot: Historical data	Anonymous	OOS
Scenario 3	Group A Materials: Lot-for-lot Group B Materials: Fixed order period, once a week Group C Materials: Fixed order period, once a month	Anonymous	First-fit
Intervention 3.1	Group A Materials: Lot-for-lot Group B Materials: Fixed order period, once a week Group C Materials: Fixed order period, once a month	Anonymous	OOS

5 Simulation

Chapter 4 provides the experiments for this research. In this chapter, we introduce the simulation model to execute these experiments. This chapter answers Question 4 '*How should the simulation model of VSM look like*?'. Section 5.1 starts with an explanation of the choice for a simulation study, and ends with a description of how the model works. Section 5.2 presents the inputs for the model. The outputs are presented in 5.3. Section 5.4 discusses the assumptions we make with the model. The verification and validation of the model is discussed in Section 5.5. In Section 5.6 we determine the number of replications to execute for a confidence interval of 95% of the outputs. Finally, Section 5.7 presents the conclusions of this chapter.

5.1 The Model

This section starts with an explanation of the choice for a simulation model. Section 5.1.2 presents the flowchart of the processes in the model

5.1.1 Motivation

The objective of this research is to find out what the consequences are of a scenario where the purchasing of buy parts is based on inventory levels, and where the buy parts are stored anonymously. Chapter 2 describes the 'system' of VSM. A system is defined as a collection of entities that act and interact towards the accomplishment of some logical end. For obvious reasons, it is not possible to experiment with the current system of VSM. Fortunately there are multiple ways to study a system as Sawicki et al. (2016) show in Figure 5-1.

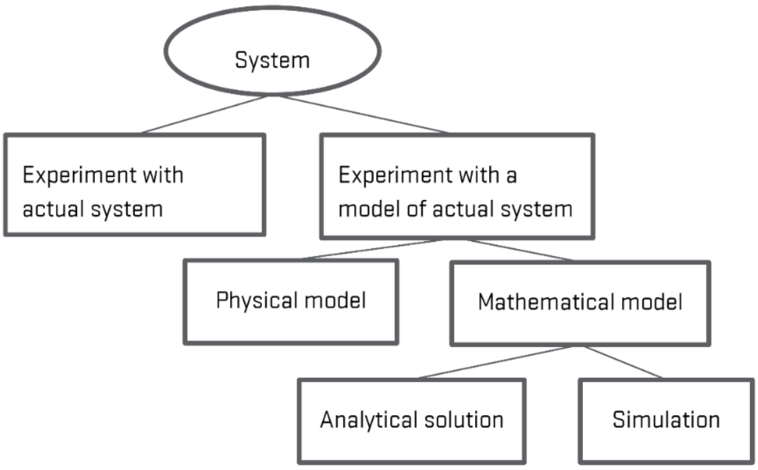


Figure 5-1 Ways to study a system retrieved from Law & Kelton, as quoted by Sawicki et al. (2016).

A simulation model has advantages over other the other ways of investigating a system. Some of the advantages Van der Aalst (2015) gives are:

- **Flexible**.
  A simulation can be adapted to any situation no matter the complexity.
- **Multi use**.
  A simulation can answer multiple questions with one model.

- **Easy to understand.**
  Little knowledge is needed to understand the modelled system. Where analytical models are abstract and require specialists to explain them.

A possible disadvantage of a simulation study is that the wrong conclusions are made based on the results of a simulation. It is important that the simulated system is a proper display of the reality, as the simulated system is almost always a simplified version of the real system.

There are multiple types of simulation models possible, all are either static models, or dynamic models. We use discrete-event simulation, modelled in Siemens Plant Simulation. Discrete-event means the system can change over time by uncertain events, making it dynamic. The changes are discrete, and are not continuous such as a chemical process. The corresponding decision tree clarifying the choice for discrete event simulation is added in Appendix F.

The different phases in a simulation study are given by Van der Aalst (2015), see Figure 5-2. In Section 1.3 we introduced the problem definition. Next, in Section 5.1.2 we present the conceptual and executable model of VSM. The simulation results are discussed in Chapter 6.

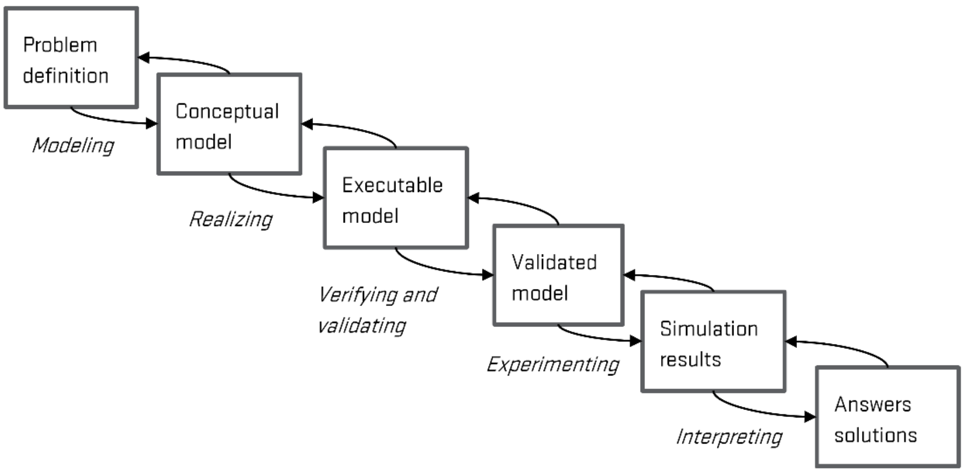


Figure 5-2 The different phases in a simulation study, adapted from Van der Aalst (2015).

5.1.2 Flowchart

The working of the model is based on the flow of goods described in Chapter 2. The warehouse activities involved in the flow of goods are translated to a simulation model with Siemens Plant Simulation. The model simulates a period of 110 working days between January and May 2017. These 110 days are the days when materials were delivered at the warehouse. Figure 5-3 shows the flow of goods used in the model.

Unloading a truck is the first process in the model. During this process, the packages containing the buy parts arrive in the system. The second process is the unpacking of the received packages. This process stores the individual materials from the packages on a moveable table. The administration of the receipt of a package is the third process in the model. We assume every package has one receipt to enter in the ERP system. A moveable table filled with unpacked materials is transported to the store/pick location in the warehouse.

In the warehouse, the materials are stored in either the AS/RS or in the VLM. This depends on the experiments. In case of an experiment with project based storage, the materials are stored in the AS/RS. In an experiment using anonymous storage the materials are stored in the VLM.

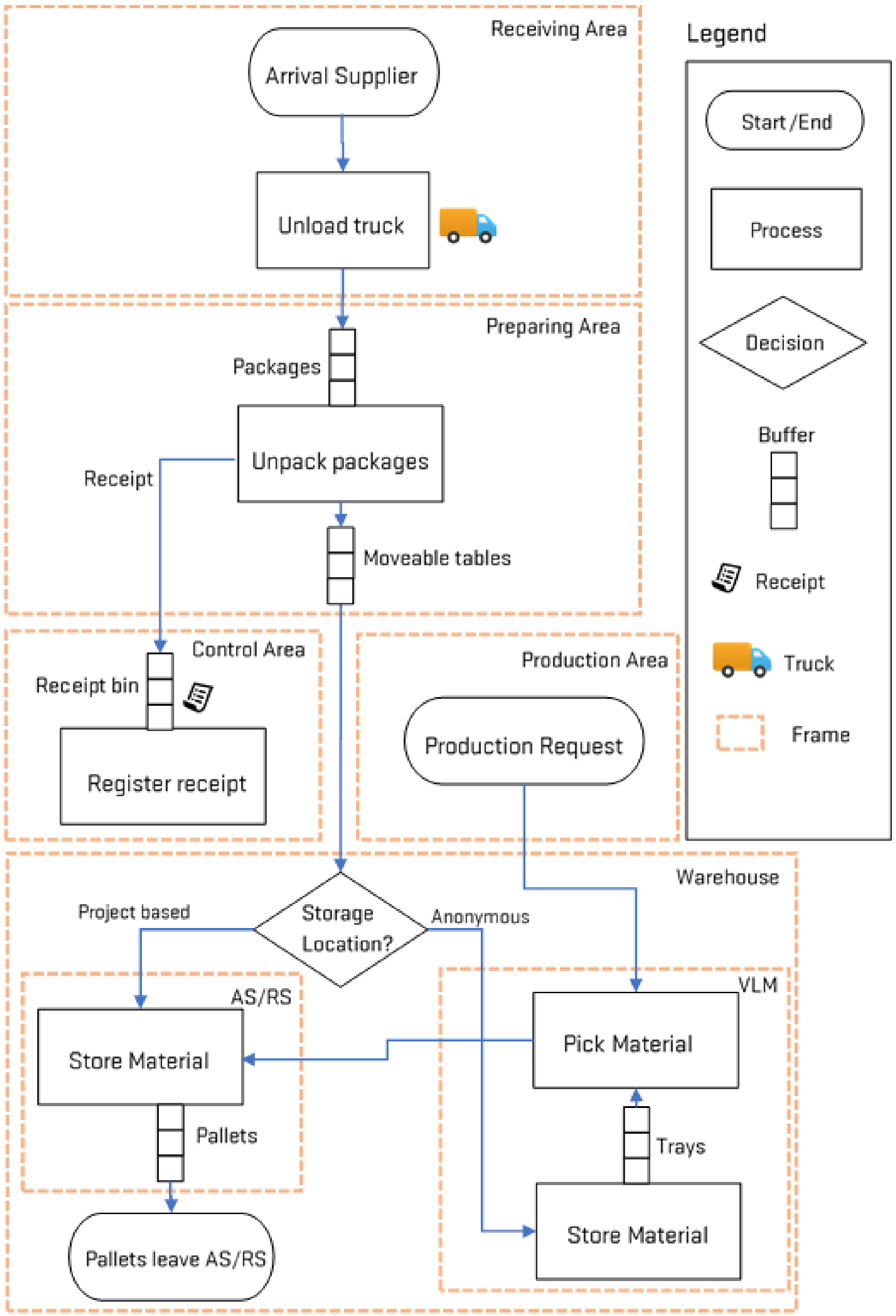


Figure 5-3 The flowchart of the processes modelled with Siemens Plant Simulation.

In case of storage in the VLM, the materials are picked later, and then stored in a project pallet. The last process in the model is the executing of a production request. This process exports the project pallets needed for the production request from the warehouse out of the system.

In the model the trays of the VLM have no fixed layout, every material can be stored in any tray if there is capacity available. A fixed layout per tray is not realistic without considering all buy parts. The storage strategy for the VLM is closest open location, materials are stored in the first available tray with enough capacity. The available capacity of the pallets, trays, and moveable tables is updated whenever a material is stored or retrieved from it. Together with the stakeholders we estimate the dimensions of the buy parts. The model uses these dimensions to determine the available capacity in the pallets, trays, and moveable tables.

5.2 Input

The simulation model requires input to deliver a certain output. The input needs to be adjustable to simulate different scenarios. The model of VSM has the following inputs:

- The delivery schedule providing the inbound flow of materials.
- The production request schedule.
- The processing times of activities.

5.2.1 Delivery Schedule

The model constructs a delivery schedule from a set of historical data. This set of historical data contains the arrival data of the buy parts during the period January 2017 – May 2017. The delivery schedule is a list containing the suppliers arriving per day, and the materials in the delivery. The model uses this list to generate the inbound flow of materials. We assume suppliers arrive always between 07:30 and 16:30. The precise arrival times are not known in advance, but randomly generated with an average arrival time of 11:00. The delivery schedule does not take growth or seasonal changes into account, Section 7.3 discusses this limitation.

5.2.2 Production Requests

We construct a production request schedule for the projects present in the delivery schedule. For every project, we trace the date the production request is made. This data is not recorded and only available in the e-mailbox of the warehouse department. The production request schedule in the model uses the dates that correspond with the historical data. The model generates pick requests a day prior to the production request of a project. The exact arrival times of production and pick requests is unknown. Table 5-1 shows the time windows that the model uses. We assume pick requests are executed mostly in early in the morning before the suppliers arrive. Production requests are executed throughout the day, with the assumed average time early in the afternoon.

Table 5-1 The time windows for the three arrival processes.

Arrival	Time window
Delivery	07:30 – 16:30 average at 11:00
Pick request	06:01 – 16:30 average at 8:30
Production request	08:00 – 16:30 average at 13:30

5.2.3 Processing times

The processes discussed in Section 5.1 have different processing times. Unfortunately, there is no data about the processing times for the unloading, unpacking, administrating, and storing of the materials available. Due to the lack of data, and because the model simulates only a selection of the total work, the model uses estimated processing times. In consultation with the stakeholders we estimate the lower bound, upper bound, and most likely time needed for each process. The simulation model uses a so called triangular distribution to generate random processing times based on the estimated lower bound *a*, upper bound *b*, and most likely value *c*. Figure 5-4 shows the probability distribution plot of this random triangular distribution. Table 5-2 shows the estimations of the processing times the model uses.

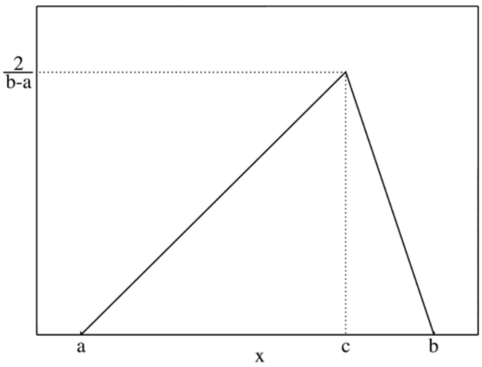


Figure 5-4 The probability distribution plot of a triangular distribution.

Table 5-2 The estimated processing times used in the simulation model.

	Time estimation		
Process	a	b	c
Unloading Regular	120s	1200s	480s
Unloading Parcel	60s	600s	300s
Unpacking	120s	900s	480s
Administrating	120s	900s	480s
Store/Pick in VLM per order line	5s	60s	15s
Store in AS/RS per single material	10 seconds response time + square root of the total number of mutations for the pallet on the pick location		

In Section 4.3 we discuss the time needed for the different movements in the AS/RS, and in the VLM. The model uses a triangular distribution to determine the unknown travel times of some movements, (see Tables 4-10 & 4-11 on pages 38 & 39). We assume the crane travels on average every other cycle through the corner. The measured travel time through the corner has a relative large standard deviation compared to the average travel time. Therefore, the model uses a triangular distribution to calculate the travel time through the corner. We assume the other movements are constant with a duration equal to the measured mean travel times, given in Tables 4-10 & 4-11. Table 5-3 summarizes the estimations for the unknown travel times.

Table 5-3 The estimations of the unknown travel times per storage location, used in the simulation model.

Storage	Movement	Time estimation
AS/RS: Crane	Along the aisle	Triangular distribution with a = 5s, b = 18s, and c = 10s
AS/RS: Crane	Through the corner	Triangular distribution with a = 22s, b =27s, and c = 29s
VLM: Lift	From tray location to I/O and vice versa	Triangular distribution with a = 1s, b = 11s, and c = 5s

5.3 Output

The output values of the model are necessary to compare the performance of the different experiments. In Section 4.2 we determine the KPIs for this research. Based on these KPIs, see Table 4-3 on page 32, we define the output values of the model. Table 5-4 lists the output values of the model. The last column shows the corresponding KPI. Analysis of the outputs provides us the information needed to answer the main research question of this research.

Table 5-4 The output of the model related to the KPIs.

Output value	KPI
Average value of inventory per day	Inventory cost
Average number of store/pick cycles in the AS/RS per day	Throughput
Average number of store/pick cycles in the VLM per day	Throughput
Average number of store/pick cycles per pallet	Productivity
Average number of store/pick cycles in the AS/RS per order	Productivity
Average time spent in the warehouse by a material	Inventory time
Average time per day spent on the store/pick activities	Labor time
Average time per day spent on unloading incoming goods	Labor time
Average time per day spent on unpacking new packages	Labor time
Average time per day spent on registering receipts	Labor time
Total time spent by employees	Labor time

The moment a pallet leaves to the warehouse to the work floor the model saves the following values:

- The time spent in the warehouse per material in the pallet.
- The number of store/pick cycles this pallet made.

At the end of each day in the simulation, the model saves the following values:

- The value of the materials present in the warehouse.
- The time employees spent on the unloading incoming goods.
- The time employees spent on unpacking new packages.
- The time employees spent on the registration of receipts.
- The time employees spent on the store/pick activities.
- The number of store/pick cycles executed per storage location.

The average time per day spent on the store/pick processes is the time needed for the actual moving of the materials by an employee. The time an employee must wait for a pallet or tray to arrive on the pick location is not included in this time. The magnitude of this waiting time is monitored with the number of store/pick cycles per storage system. At the end of each run, at day 110, the model calculates the averages per day of these values:

- The average value of inventory per day.
- The average number of store/pick cycles per pallet.
- The average number of store/pick cycles per project.
- The average time a material spent in the warehouse.
- The average working times per day per activity.

5.4 Assumptions

The simulation model is a simplified version of the real world. To prevent the model becoming unnecessarily complex, we make assumptions in correspondence with the stakeholders. The model assumes the following:

- From all deliveries, 30% is a parcel delivery. Parcel deliveries require no employee to unload.
- Parts that do not fit in the AS/RS, or in the VLM, leave the system at the unpacking stage. They are not relevant for the store/pick cycles in the AS/RS and VLM.
- There are no back orders possible. The materials missing at the time of a production request stay in the warehouse if they arrive later.
- During the opening times, always three employees are present. There are no breaks.
- It takes no time for the employees to walk between the different process locations.
- The model is a 'perfect' system. Irregularities such as exchanging materials between projects do not occur.

5.5 Verification and Validation

An essential phase in the simulation study is the verification and validation process. Verification is needed to check if the programmed model corresponds with the conceptual paper model. Validation is needed to check if the programmed model corresponds with reality, see Figure 5-5. Without a decent verification and validation, the results are not reliable.

In a meeting, the Stakeholders from Purchasing, and the Warehouse Department, verified the paper model from Figure 5-3. Because the arrival process in Scenario 1 corresponds to the real system, and the flow of goods is the same as in the current situation at VSM, we run a pilot with Scenario 1 for the validation of the model. The pilot run gives an indication if the model correctly represents the real system, and if the time estimations are realistic. The stakeholders validate the simulation model based on a demonstration and by discussing the results of several pilot runs. According to the stakeholders the model seems valid.

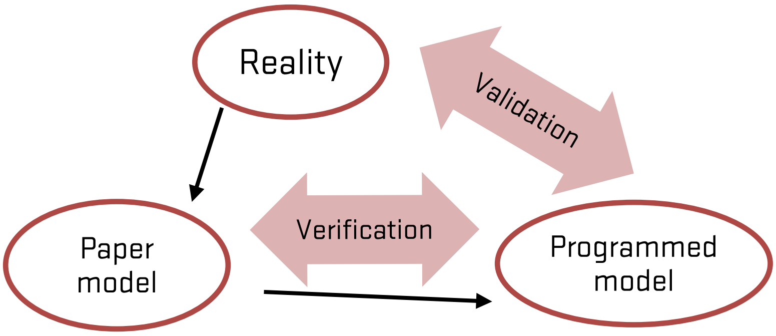


Figure 5-5 The process of verification and validation.

5.6 Run Length

The performance of the model depends on the initial conditions, this is called 'transient system behavior'. The simulation uses random number streams to determine arrival and processing times discussed in Section 5.2. The input of the model depends on the used random numbers. The model makes point estimates with these random numbers. The output of the model depends on the input. So, the output values depend on the used random numbers. As the results are based on these point estimates, and thus random, multiple replications are needed for statistical significance.

$$\mathrm{CI} = \bar{X}_n \pm t_{n-1,1-\alpha/2} \frac{S_n}{\sqrt{n}} \quad \text{with } S_n = \frac{\sum_{i=1}^{n}(X_i - \bar{X}^2)}{n-1} \tag{5}$$

Where:
$\bar{X}$ = mean of output data from the replications
$\bar{X}_i$ = result from replication i
S_n = standard deviation of the output data from n replications
n = number of replications
$t_{n-1,1-\alpha/2}$ = value from the Student's t-distribution with n-1 degrees of freedom and a significance level of $1 - \alpha/2$

We calculate a 95% confidence interval of the output values with (5) to get statistical significance. We do this for the output values average value of inventory, total time spent by employees, and the average time per day spent on the store/pick activities.

We perform replications until the width of the confidence interval, relative to the average, is sufficient small. We select the number of replications where the interval reaches and remains below a 5% level of deviation. The formula to calculate the minimal number of runs n^* is the following:

$$n = min\left\{ i \geq n : \frac{t_{i-1,1-\alpha/2} \frac{S_n}{\sqrt{i}}}{|\bar{X}_n|} \leq \frac{\gamma}{1+\gamma} \right\} \tag{6}$$

Where:
i = replication number
n = smallest i for which the formula applies
γ = relative error

For every experiment, we calculate n with formula (6). The smallest value of n that holds (6) in every scenario for every output value is 20. The model makes twenty independent replications per experiment. An example of a calculation is added in Appendix F.

5.7 Conclusion

In this chapter, we motivate the choice for a simulation study, and introduce the simulation model of VSM. The model represents the flow of goods in the warehouse of VSM. The input of the model consists of a delivery schedule containing all order lines. The model uses random numbers and a triangular distribution to determine the exact times for the arrival of the materials. The processing times per activity are variable, but delimited with a lower and upper bound.

The output that the model produces corresponds to the KPIs in Table 4-3. Every experiment simulates 110 working days. Twenty independent replications per experiment provide a confidence interval of 95% for the output values.

Next, Chapter 6 discusses the results of the experiments executed with the simulation model.

6 Analysis of Results

At this stage we know how the simulation model of VSM looks like. This chapter discusses the results of the different experiments with the simulation model. Section 6.1 describes the method to calculate statistical significance of the results. The performance of the current situation, measured with Scenario 1, is presented in Section 6.2. Section 6.3 discusses the results of a change to anonymous stock, measured with Scenario 2. Section 6.4 presents the results of Scenario 3, where next to anonymous stock, also 'ABC Replenishment' is applied. The performance of the OOS strategy for the VLM is discussed in Section 6.5. Section 6.6 discusses the consequences of the different scenarios on the flexibility at VSM. Finally, Section 6.7 summarizes the results.

6.1 Statistical Reliability

Some of the average output values of the different scenarios differ only a fraction. Differences are analyzed with the confidence interval approach for independent data. This approach constructs a confidence interval of 95% for the differences in the observations between two experiments of an output value. The outputs are significant different if the T-test value lies outside of the confidence interval. The confidence interval is calculated with (7).

$$CI = \bar{W} \pm t_{n-1,1-\alpha/2} \sqrt{Var[\bar{W}]} \qquad \text{with } Var\,[\bar{W}] = \frac{1}{n(n-1)} \sum_{j=1}^{n} [W_j - \bar{W}]^2 \tag{7}$$

Where:

$\bar{W}_j = X_j - Y_j =$ The difference between observations of two experiments

$X_j =$ The output of experiment X in run j

$Y_j =$ The output of experiment Y in run j

$\bar{W} = \frac{1}{n} \sum_{j=1}^{n} W_j$

6.2 Current performance

The performance of Scenario 1 is used as a reference for the possible consequences of a change in storage strategy, and replenishment strategy. The arrival process of materials is equal to the historical data, and the flow of goods is equal to the current flow of goods in the warehouse of VSM. All materials are stored directly in a project pallet, leading to an average of 23.5 pallet movements per day, and an average store/pick time per day of 45 minutes. The average number of pallet retrievals per project is 5.6. The VLM is not used.

Between January 2017 and May 2017, a total of 690 deliveries are made, on average 6.2 deliveries per day. Only a fraction of all materials is considered, so the actual total number of supplier deliveries at VSM is higher. The simulated average value of the inventory per day is € 1,415,017. Materials spent on average 11.2 days in the warehouse before they leave to the production area. This is more than double the needed time with the rule of one workweek before the start of production, discussed in Section 2.2.1 on page 10. The total working time spent by employees during the simulated 110 days is 21.36 days.

Figure 6-1 shows the division of working time over the different activities. Only 9% of the working time is spent on store/pick activities.

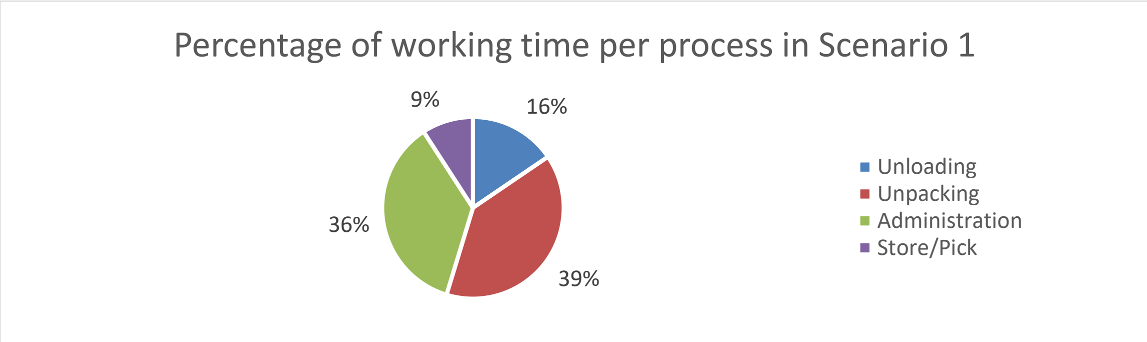


Figure 6-1 The percentage of average working time spent on the different processes during a day in Scenario 1.

6.2.1 Intervention 1.1

The goal of Intervention 1.1 is to reduce the number of pallet retrievals per project. The arrival process in this intervention is changed such that all materials of a project are delivered on the same day. This leads to an average of 7.1 deliveries per day. Almost one delivery per day more compared to 6.2 deliveries per day in Scenario 1. This is explained by the fact that suppliers visit VSM more often, with less packages at a time. This arrival process is not realistic to happen in the real system.

The number of pallet retrievals per project decreases from on average 5.6 pallet retrievals per project to an average of 4.3 pallet retrievals per project. Notable is the reduction in the average number of pallet movements per day. This number reduces to 14.3 pallet movements per day. A significant reduction compared to the 23.5 pallet movements per day in Scenario 1.

The average value of inventory decreases significantly, from more than € 1.4 million to less than € 350,000. This reduction of 75% is partly explained with the absence of a backlog in this intervention. In Intervention 1.1, all materials arrive before the day of the production request, where as in Scenario 1 some materials arrive a few days after the production request of the order. These materials stay in storage the rest of the days, increasing the average value of inventory per day. The average time spent in the warehouse by a material is 65% less than in Scenario 1. The average working time per day reduces only a little, from 4.7 hours to 4.5 hours. Table 6-1 gives a comparison of the output values between Intervention 1.1 and Scenario 1.

Table 6-1 Comparison of the output values between Scenario 1 and Intervention 1.1.

Output	Scenario 1	Intervention 1.1
Average value of inventory per day	€ 1,415,017	€ 339,511
Average time spent in warehouse per material in days	11.2	3.9
Average number of store/pick cycles per pallet	3.2	2.4
Average number of store/pick cycles in the AS/RS per order	5.6	4.3
Average number of store/pick cycles in the AS/RS per day	23.5	14.3
Average working time per day in hours	4.7	4.5

6.2.2 Intervention 1.2

The goal of Intervention 1.2 is to reduce the number of deliveries by using a fixed delivery day per supplier. The result is an average of 3.8 deliveries per day, a reduction of 39% compared to the average of 6.2 deliveries per day in Scenario 1. The differences of the average number of pallets per project, and pallet retrievals per project, between this experiment and Scenario 1 are not significant.

The working time needed per day is less with this intervention. From 4.7 hours per day in Scenario 1 to 3.8 hours per day in Intervention 1.2, a reduction of 18%. There are less deliveries, but the size of the deliveries is bigger. Because of these bigger deliveries, employees profit from economies of scale, and the time needed in the first stages of the flow of goods is less. The average store/pick time per day is not significant different compared to the average store/pick time per day in Scenario 1.

Table 6-2 The most outstanding differences in output values between Scenario 1 and Intervention 1.2.

Output	Scenario 1	Intervention 1.2
Average number of deliveries per day	6.3	3.8
Average working time per day in hours	4.7	3.8
Average unloading time per day in minutes	43	27
Average unpacking time per day in minutes	109	92
Average administration time per day in minutes	101	85

6.3 Anonymous Storage

In Scenario 2 the flow of goods is based on anonymous storage. With the anonymous storage, the materials are stored in the VLM first. The arrival process is equal to the one in Scenario 1, only the materials are now 'free to use'. This reduces the average unpacking time per day, and the time needed for the administration of the receipts with more than 16%. Because now the same materials can be stored in the same location, and not in separate project pallets. In the ERP system only 1 procurement order needs to be administrated, instead of multiple smaller orders containing the same material. In contrast, the needed store/pick time per day increases with 50%. That is because anonymous storage requires two more activities than project based storage, as Section 4.5 describes. Despite this increase of 50%, the average working time needed per day reduces with approximately 8%. Figure 6-2 shows the division of the working time per day over the different processes in Scenario 2.

Table 6-3 compares the results of Scenario 2 with the results of Scenario 1. The value of inventory per day decreases with 18% compared to Scenario 1. The decrease in the average value of inventory, and the increase in average time in the warehouse per material, seem to contradict.

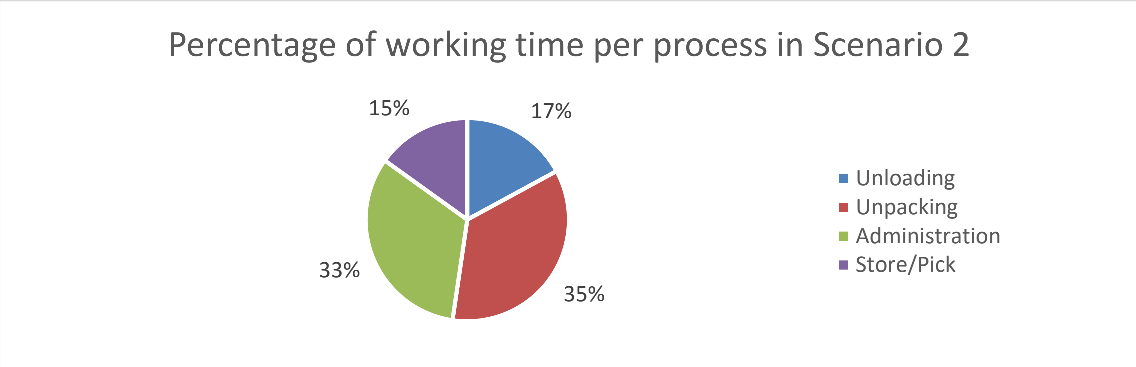


Figure 6-2 The percentage of working time spent on the different processes during a day in Scenario 2.

We think because the expensive materials stay in the warehouse shorter, the average value of inventory reduces. With the picking process, materials that arrived the earliest are picked first. As a result, the materials leaving the warehouse have stayed in the warehouse longer on average.

The VLM has on average 15.2 store/pick cycles per day. The average number of pallet movements per day reduces from 23.5 to 9.9. The total number of store/pick cycles per day compared to Scenario 1 is only 2 more, 25.1 versus 23.5. The operating time of the VLM is faster than the AS/RS, see Section 4.5. The average number of pallet movements per project reduces from 5.6 in Scenario 1, to 3.1 in Scenario 2. This is even less than the average of 4.3 pallet movements per project in Intervention 1.1. In Intervention 1.1 the materials arrive still on a different time of the day, where in Scenario 2 the materials are picked and then stored at all at the same time. This is an advantage of the anonymous storage over the project based storage.

Table 6-3 Comparison of the output values between Scenarios 1, 2, and 3.

Output	Scenario 1	Scenario 2	Scenario 3
Average value of inventory per day	€ 1,415,017	€ 1,151,533	€ 1,192,370
Average number of store/pick cycles per pallet	3.2	1.3	1.3
Average number of store/pick cycles in the AS/RS per order	5.6	3.1	3.0
Average number of pallets used per project	1.8	2.3	2.3
Average number of store/pick cycles in the AS/RS per day	23.5	9.9	9.6
Average number of store/pick cycles in the VLM per day	0	15.2	13.4
Average time spent in the warehouse per material in days	11.2	14.6	18.8
Average working time per day in hours	4.7	4.3	2.5
Average unloading time per day in minutes	43	44	24
Average unpacking time per day in minutes	109	91	49
Average administration time per day in minutes	101	84	45
Average store/pick time per day in minutes	26	39	30

6.4 Anonymous Storage and ABC Replenishment

Table 6-3 shows the results of Scenario 3 compared to the two other scenarios. In Scenario 3 both anonymous storage, and the replenishment strategy suggested in Section 4.3, are used. The new replenishment strategy leads to an average of 3.4 deliveries per day, instead of 6.3 with the current used lot-for-lot strategy. This reduces the working time needed per day to 2.5 hours, a reduction of more than 40% compared to Scenarios 1 and 2. Figure 6-3 shows the division of working time per task in Scenario 3. This division is quite different compared to Scenario 1. With anonymous storage and ABC Replenishment, 20% of the working time per day is spent on store/pick activities. A lot more compared to the 9% of working time per day in case of project based storage and lot-for-lot replenishment. The ABC Replenishment causes a great reduction in the time needed for unpacking. Because materials do not have to be sorted per order, and only one receipt is needed for the administration the average time needed per day for these activities reduces with more than 50%.

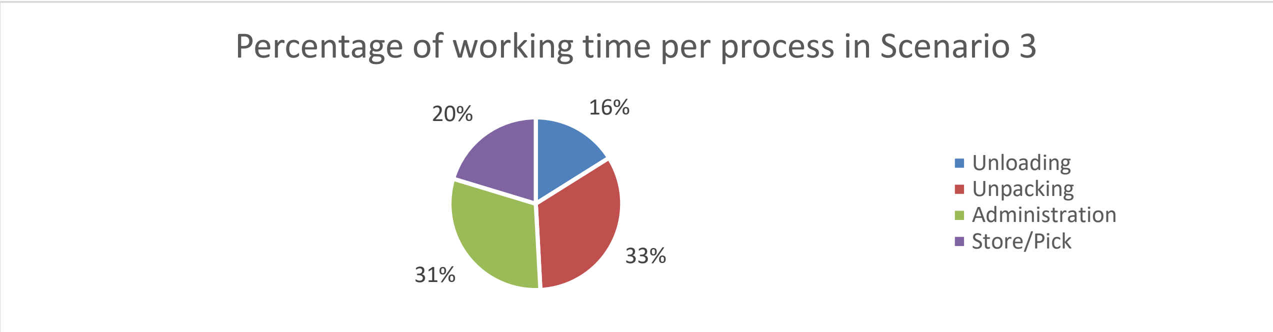


Figure 6-3 The percentage of working time spent on the different processes during a day in Scenario 3.

The materials classified as 'C' are ordered once a month with the used replenishment strategy. This leads to a longer average time spent in the warehouse per material. Because 'C' materials have a low cost per piece, the average value of inventory increases only with 3.5% compared to Scenario 2. Compared to Scenario 1 the average value of inventory decreases with 15%.

6.5 OOS Storage in VLM

The goal of Interventions 2.1 and 3.1 is to reduce the time needed for the store/pick activities, by using OOS for storage design in the VLM. The results of Interventions 2.1 and 3.1 show decrease in the average store/pick time needed per day, of only 2 to 3 minutes. This is a reduction of only 1% of the total time needed in per day.

Remarkable enough the number of store/pick cycles for the VLM increases. We think this is because the put away activity of materials in the VLM requires more trays with OOS. The number of store/pick cycles at the AS/RS reduces only a fraction. The other output values show no significant differences. Table 6-4 shows the differences in performance when using OOS for the storage in the VLM.

Table 6-4 The differences between anonymous storage in the VLM with first fit, and with OOS.

Output	Scenario 2 First fit	Intervention 2.1 OOS	Scenario 3 First fit	Intervention 3.1 OOS
Average value of inventory per day	€ 1,151,533	€ 1,150,750	€ 1,192,370	€ 1,188,954
Average number of store/pick cycles in the AS/RS per day	9.9	9.4	9.6	9.5
Average number of store/pick cycles in the VLM per day	15.2	18.2	13.4	14.7
Average store/pick time per day in minutes	39	36	30	28

6.6 Flexibility

This section discusses consequences of the different storage strategies, and of the different replenishment strategies, on the flexibility. In Section 4.5 we define the AS/RS as the bottleneck in the put away and pick activities. With anonymous storage, the average number of store/pick cycles per day in the AS/RS is reduced with more than 50%. The total number of store/pick cycles per day increases slightly with anonymous storage, see Figure 6-4.

The experiment with the lowest total average number of store/pick cycles per day is Intervention 1.1. Intervention 1.1 is also the least suited for implementation. Therefore, we look for the experiment with the lowest average number of store/pick cycles in the AS/RS, as this is the defined bottleneck, we see that anonymous storage is the best storage strategy.

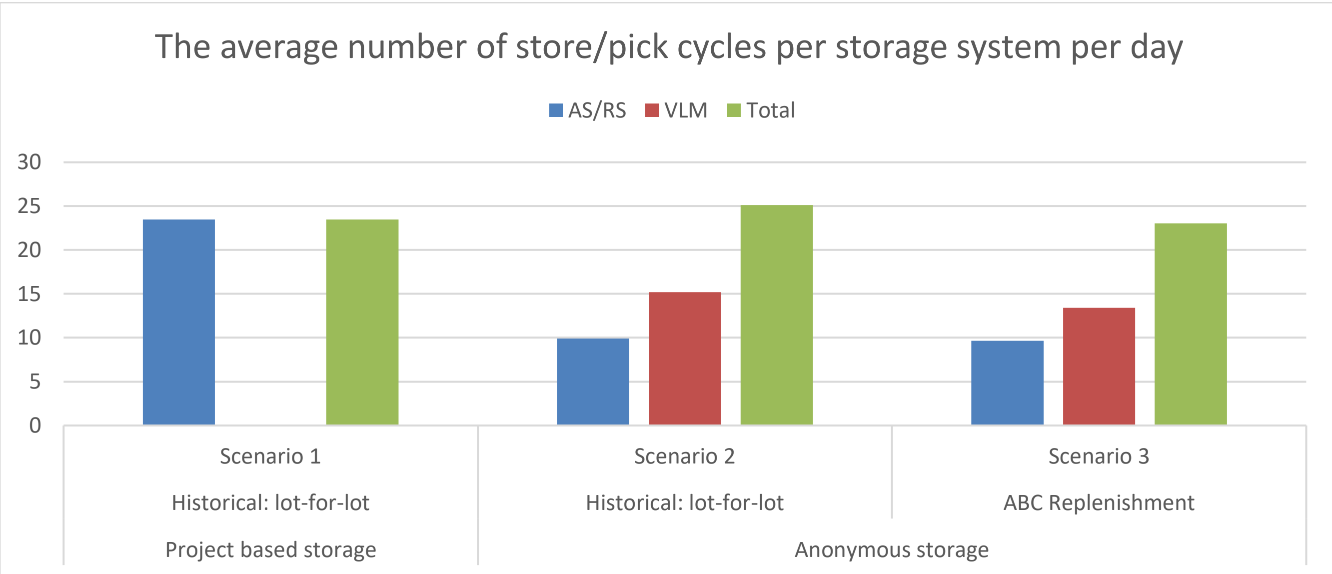


Figure 6-4 Overview of the number of store/pick cycles per storage strategy.

The experiments use in total four different replenishments strategies. Table 6-5 shows the details of the arrival process with the different strategies. The ABC replenishment strategy is only possible in combination with anonymous storage. This strategy reduces the total number of order lines over the simulated period with more than 50% compared to the current used lot-for-lot strategy. The purchasing and finance departments will spend less time on invoicing if there are less orders.

Table 6-5 Overview of the results per replenishment strategy.

Replenishment strategy	Scenario	Storage	Average no. of deliveries per day	Average no. deliveries per material	Total number of order lines
Historical: lot for lot	1	Project based	6.3	10.0	± 4800
1 Arrival day per order	1.1	Project based	7.0	20.3	± 4800
Fixed delivery day	1.2	Project based	3.8	8.4	± 4800
Historical: lot for lot	2	Anonymous	6.3	10.0	± 3500
ABC Replenishment	3	Anonymous	3.4	5.5	± 2000

Figure 6-5 shows the influence of the replenishment strategy on the first stages in the flow of goods. In the first stages in the flow of goods the materials are unloaded and unpacked. The average time needed per day for the unloading and unpacking activity reduces a lot with the ABC Policy. This reduction is more than the extra time needed for the order picking.

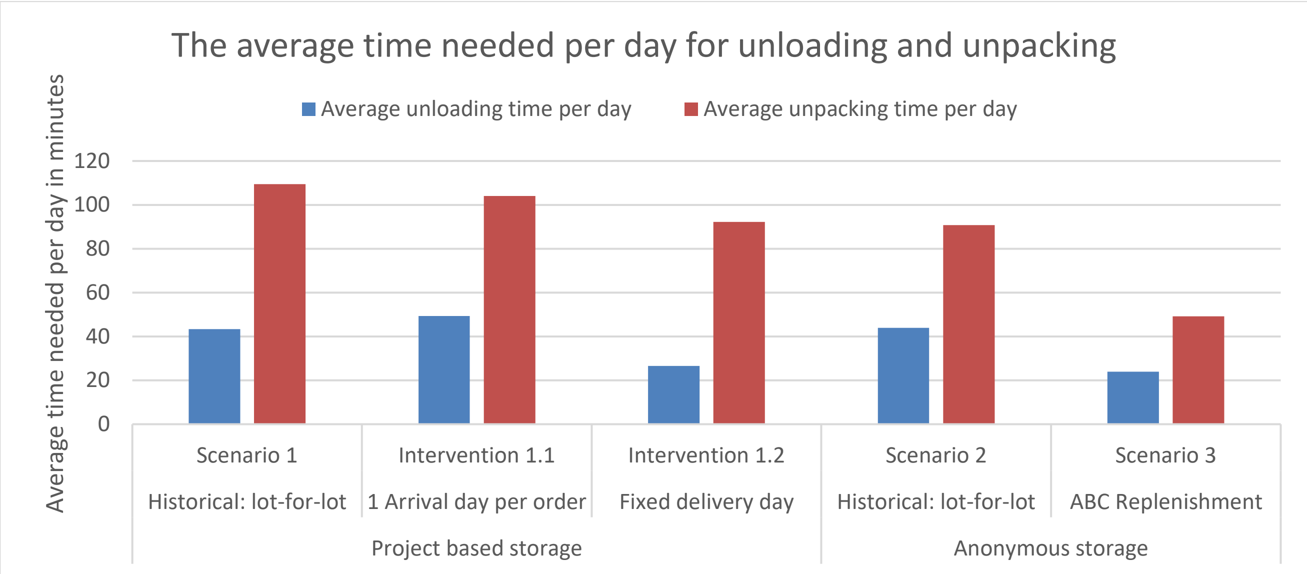


Figure 6-5 The average time needed per day for unloading and unpacking per replenishment strategy.

6.7 Conclusion

This chapter presents and discusses the results of the experiments with the simulation model. In the current situation VSM uses project based storage and a lot-for-lot replenishment strategy. This leads to an average of 6.3 deliveries per day. The average value of inventory is around 1.4 million, and the average working time needed per day is 4.7 hours. Using a fixed delivery day for the suppliers reduces the average working time needed per day to 3.8 hours, due to economies of scale for the unloading and unpacking activities.

A change to anonymous storage reduces the usage of the AS/RS. The number of store/pick cycles in the AS/RS reduces from an average of 23.5 cycles per day to 9.9 cycles per day. The average value of inventory per day reduces with 18%. Anonymous storage requires only an average of 4.3 hours of working time per day. The division of the time needed changes with more time needed for store/pick activities, and with less time needed for administration.

Replacing the lot-for-lot strategy with an ABC Replenishment strategy reduces the average number of deliveries per day to only 3.4 deliveries. The combination of anonymous storage and ABC Replenishment performs significantly better than the current situation. This combination reduces the average work needed per day with more than 40%, to only 2.5 hours. The average value of inventory reduces with 15% to around 1.2 million. The usage of OOS for the VLM leads not to a significant better performance. The flexibility increases the most with the combination of anonymous storage and an ABC Replenishment strategy.

Next, Chapter 7 concludes this research and answers the main research question.

7 Conclusion and Recommendations

Now that the results of the experiments are known, we answer the main research question in this final chapter. Section 7.1 gives the conclusion for this research. Section 7.2 gives recommendations to VSM how to gain advantages from this research. In Section 7.3 we discuss the limitation of this research. This chapter ends with a suggestion for future research in Section 7.4.

7.1 Conclusion

The goal of this research is to gain knowledge on the (dis)advantages of inventory based ordering in combination with anonymous storage, for the buy parts. The research question used to achieve this goal is:

What are the consequences for VSM, in particular for the Warehousing Department, if the procurement of buy parts will be based on inventory levels, and if the storage of buy parts will be anonymous, and how should this be implemented?

A set of 373 buy parts is used as sample for the analysis. By analyzing the current situation at VSM, the flow of goods in the warehouse of VSM is identified. Incoming buy parts are stored in a project pallet in the AS/RS. Because of this project based storage, the picking process is combined with the put away activity. The VLM in the warehouse is currently used for spare parts and bulk materials. The flexibility is described with several processes such as the retour process and the installed base.

We adapt the overview of Staudt et al. (2015) about common used performance indicators for warehouse operations in a Make to Stock environment, to performance indicators for warehouse operations in the ATO_{ED}, MTO_{PD} environment of VSM. The average value of inventory, the labor time, and the utilization of the warehouse are the KPIs that follow from this overview.

The two important storage locations in the warehouse of VSM, the AS/RS and the VLM, are used properly according to the literature. With a time study the AS/RS is defined as the bottleneck. Based on time measurements the AS/RS is defined as the bottleneck in the store/pick activities. The flow of goods with anonymous storage therefore uses the VLM as first storage location.

Literature on inventory management reveals it is common to use different strategies for different groups of materials. Multiple criteria inventory classification is used to group the materials. The used criteria are the demand per year, and the cost per piece. For materials of group A, the current used lot-for-lot strategy remains. The materials of Group B should be replenished with a Fixed Order Period strategy. And for the materials of Group C a EOQ strategy is suggested, where the order quantity is determined with the common used EOQ formula.

To research the consequences of a different storage and replenishment strategy, a simulation study is done. With the simulation model different combinations of replenishment and storage strategies are observed. The combination of anonymous storage and ABC Replenishment gives the best performance. Compared to the current situation this strategy reduces the average working time needed per day in the warehouse with more than 40%. The average value of inventory reduces with 15%. And the usage of the bottleneck, the AS/RS, reduces with more than 50%. The influence on the flexibility is not directly measurable, but because materials are 'free to use' with anonymous storage, the flexibility increases. In Section 7.2 we give answer to the last part of the research question: *how should this be implemented*.

7.2 Recommendations

To benefit from the results of this research VMS should change the storage towards anonymous storage. A VLM with sufficient capacity is needed. Fortunately, VSM has two unused VLMs available at another location, so no big investments are needed. The AS/RS should be used as efficiently as possible. Using anonymous storage in a VLM, and picking the materials needed per project from the VLM, the AS/RS usage reduces.

The current processes cannot be changed overnight. We recommend running a pilot of five months with the group 'C' buy parts subject of this research. For these materials some settings like the lot-for-lot order quantity need to be adjusted in the ERP system. For these group C materials, a Fixed Order Period strategy, with an order period of four weeks, is suggested. If the results during the pilot are positive, all used buy parts should be classified with the multiple criteria inventory analysis, and the new materials of Group C should be included in the remainder of the pilot. After the pilot of five months VSM should evaluate the pilot. Based on those results further actions can be taken. When VSM fully implements the anonymous storage and ABC replenishment after the pilot, it is important to reevaluate the materials over time. The materials in group A and B, every six months, and the group C materials every year (Flores & Whybark, 1987).

Another recommendation is to use fixed delivery days for suppliers. Some suppliers already have a fixed delivery day, where other suppliers visit VSM multiple days per week. The results of this research show that economies of scale can be achieved with using a fixed delivery day per supplier. The changes not only influence VSM, but also their suppliers need some time to adapt to a different replenishment strategy.

The third recommendation is to gather more data regarding the flexibility, and processing times. The problems with exchanging the materials between projects are not monitored, but these numbers could give an indication of possible savings that can be achieved. By monitoring the processing times of the activities in the warehouse bottlenecks can be revealed and reduced. It is as they say, to measure is to know.

7.3 Limitations

The last recommendation in Section 7.2 indicates one of the limitations of this research. Due to the lack of available data about processing times, the simulation model uses estimations. Due to these estimations, the absolute values of the used times per activity are not reliable.

The simulation model uses a fixed delivery schedule per scenario, based on the historical data of five months. These five months are not representative enough for the future if the number of sales increases the coming years. Because only a part of the actual flow of goods is simulated, it is unknown if the current storage capacity of the VLMs is sufficient to store all buy parts.

The flexibility cannot be directly measured, and the influences of anonymous storage on the flexibility is discussed but not quantified.

In the simulation model there are always three employees available during opening hours, and no breaks are taken. This is not realistic and might affect the actual performance.

7.4 Future Research

The results of Interventions 2.1 and 3.1 show no significant improvement when using OOS for the VLM. If VSM decides to run a pilot, as Section 7.2 discusses, a study focused on the use of the VLM can be done. With this study different strategies regarding input, and output optimization can be examined.

The results of this research indicate that savings can be made with an anonymous storage strategy for buy parts. It might be possible to realize more savings if also the make parts are treated in a different way.

Since the last year every process in every company is being automated or digitalized, but the incoming goods at VSM are entered in the ERP system manually. Research on the use of barcodes, or other common used strategies for administration processes, could lead to an improvement for this manual process. This would not only save time, but also reduces the probability of errors.

The current used strategy for storage on the floor is based on the experience of the employees. In literature there are several techniques available, such as the optimal lane depth property by M. Goetschalckx and Ratliff (1991). Using such a strategy could reduce the time needed for the storage and retrieval of materials stored on the floor.

In Chapter 2 the After Sales Department is mentioned briefly. This department has their own replenishment process for the spare parts. This means there are two departments, physically separated between different offices, purchasing the same materials, at the same suppliers. It is interesting to research what profits from economies of scale can be achieved for these parts by uniting the replenishment processes of both departments.

Section 2.1 mentions the component commonality between modules. Most materials are used in only one module. During the literature research we found two interesting articles on cost benefits by component commonality between products by Hillier (2000, 2002).

Currently all materials are transported to the work floor in pallets. Battini, Faccio, Persona, and Sgarbossa (2009) wrote an article about the optimal feeding policy in an assembly system. When the project for the reduction of lead times, mentioned in Section 2.2.1, is finished, multiple operation steps are used for the delivery dates of materials. Because of these multiple delivery dates the pallets transported to the work floor will contain less materials. Then a study on optimal feeding policy is even more interesting.

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Appendix A Machines, Modules, and Materials

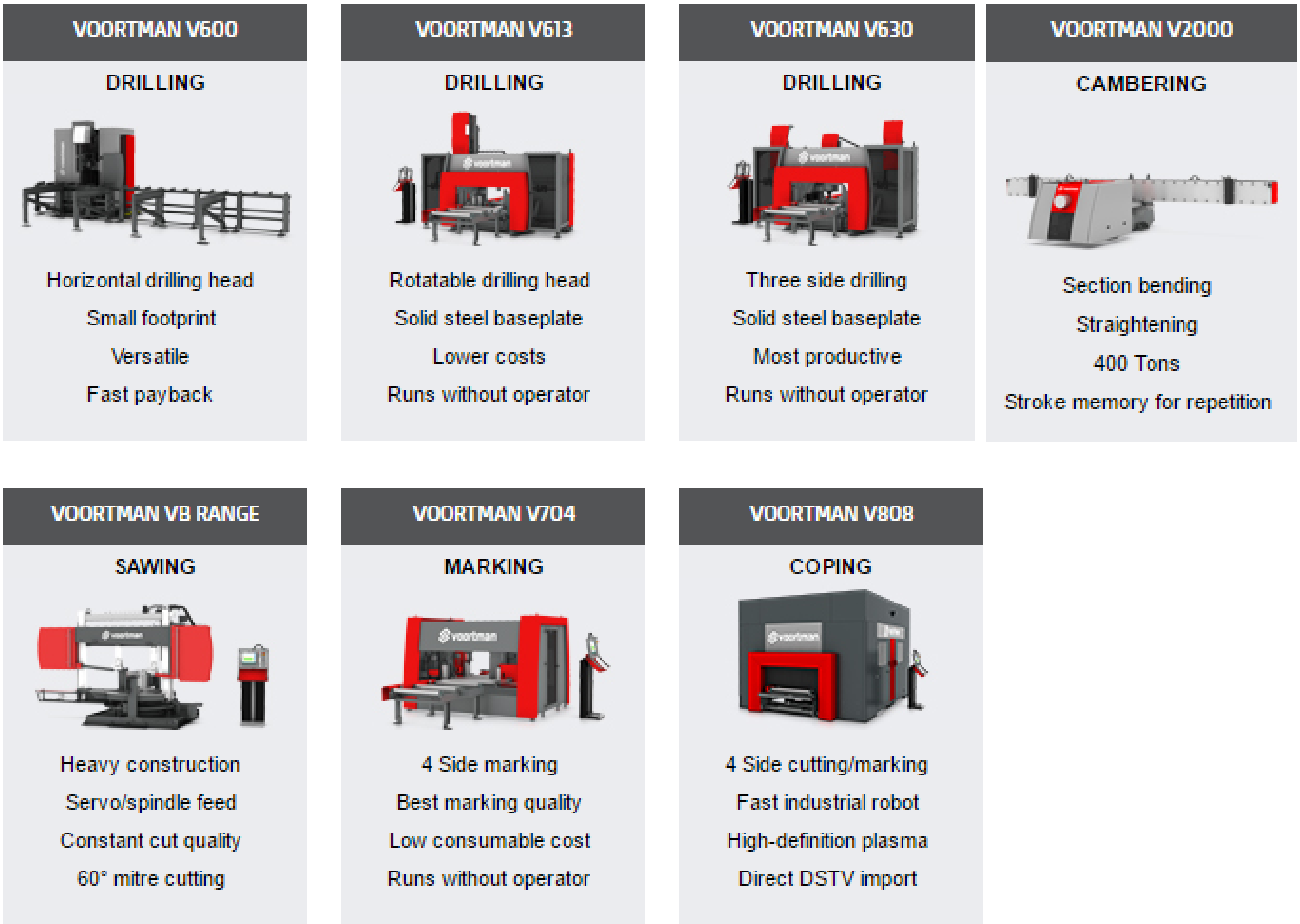


Figure A-1 Beam processing machines.

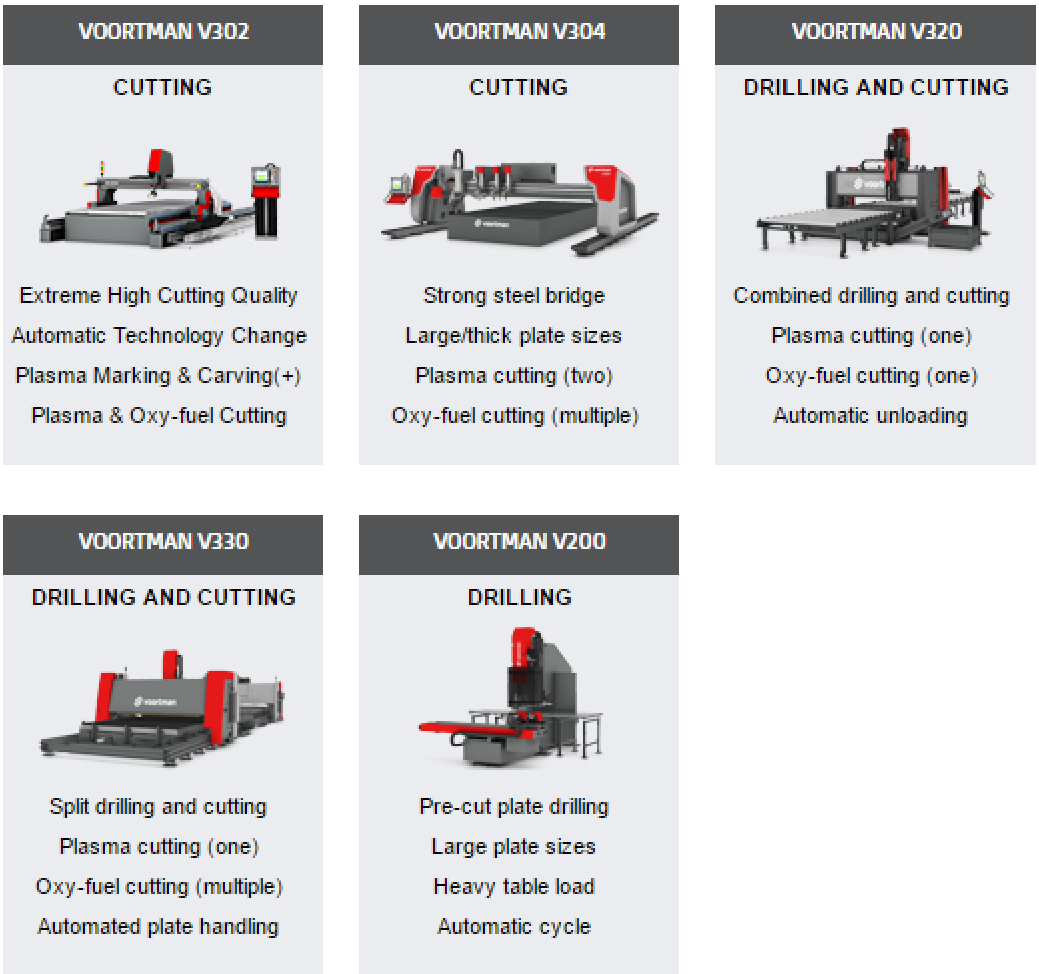
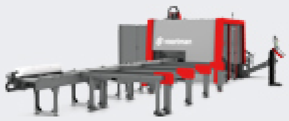


Figure A-2 Plate processing machines.

VOORTMAN V550

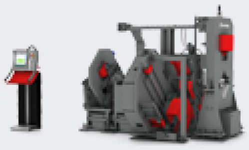
PUNCHING AND SHEARING



Flat and angle processing
High pressure hydraulics
Layout marking
Automated handling

VOORTMAN V505-250T

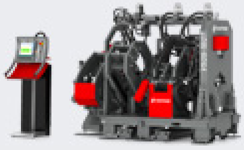
PUNCHING AND SHEARING



Tower industry
High production volume
High pressure hydraulics
Carbide drilling

VOORTMAN V505-160T

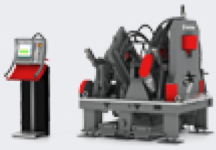
PUNCHING AND SHEARING



Fully automated
High speed production
Minimal waste
Easy tool changing

VOORTMAN V505M

PUNCHING AND SHEARING



Steel fabricators
Clip angles
Flat bar processing
Automated handling

VOORTMAN V70

NUMBERING

6 character numbering
Manual operation
Highly visible numbers

VOORTMAN V3100

STORAGE

Saves prescious floorspace
Organized material storage
Easy manual operation

Figure A-3 Flat angle processing machines.

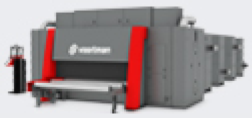
VOORTMAN VSB RANGE

SHOT BLASTING

High power turbines
Long component life
Easy maintenance
Runs without operator

VOORTMAN VP RANGE

PAINTING



Solvent and water-based
Minimal overspray
Easy cleaning
Pre-heating and drying

Figure A-4 Surface treatment machines.

Table A-1 Number of shared modules per number of materials.

Number of shared modules	Number of materials
1	331
2	30
3	10
4	2

Table A-2 The modules used for the selection of buy parts.

Module	Module description	# buy parts
000-2199	V600 Base (cabin)	61
003-4905	Cable chain Y for gantry 4000 plasma	12
003-5958	Cable chain Y for gantry 4000 oxy	14
004-1459	V304 Gantry 5000	31
004-1478	V304 Carriage variably dragged 130	13
004-1482	V304 Plasma bevel	28
004-2531	V808M Feederrolls type 2	75
004-3045	Movable tables V808M Left	20
004-3046	Movable tables V808M Right	20
004-3358	Oxygen cutting parts V808M	48
004-3359	Plasma Hypertherm HPR260-400XD V808M	27
004-5105	Plasma Kjellberg SF300 (V808)	28
004-7873	V808M Coping system type 2	52

Appendix B Order Process

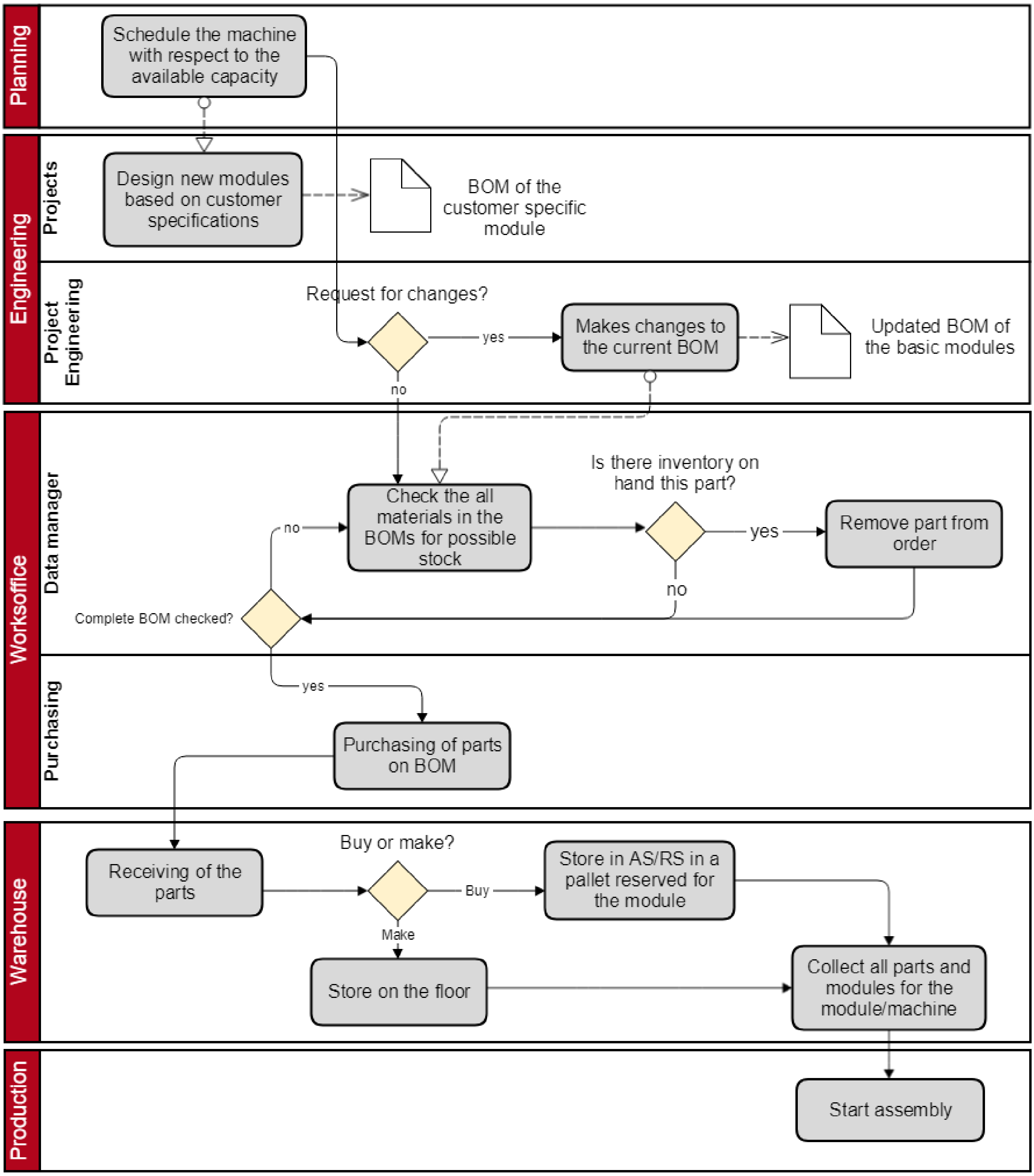


Figure A-1 Order process at Voortman Steel Machinery (authors illustration).

Appendix C Stakeholder Analysis

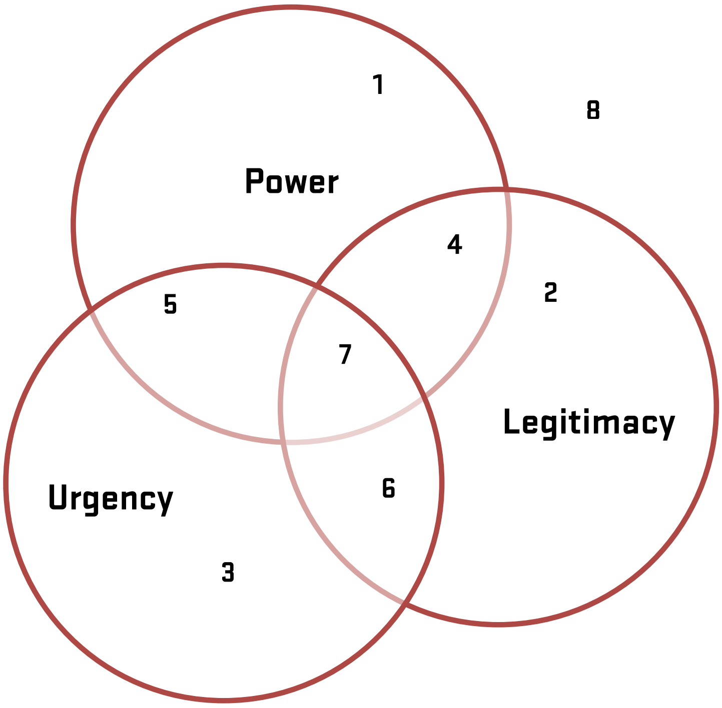


Figure C-1 The Stakeholder Framework of Mitchell et al. (1997)

Table C-1 The different types of stakeholders according to Mitchell et al. (1997)

No.	Stakeholder
1	Dormant stakeholder
2	Discretionary stakeholder
3	Demanding stakeholder
4	Dominant stakeholder
5	Dangerous stakeholder
6	Dependent stakeholder
7	Definitive stakeholder
8	Non-stakeholder

Appendix D Performance Indicators

Table D-1 Explanation of the performance indicators.

Indicator	Description	Unit
Receiving time	The time needed to unload an incoming package	Time in minutes
Put away time	The time needed to store the material in the warehouse	Time in minutes
Order picking time	The time needed to gather the materials for a production order	Time in minutes
Delivery time	The time needed to deliver a production order to the workspace	Time in minutes
Order lead time	The total time a department spent on processing an order at the works office	Time in hours
Physical inventory accuracy	The comparison between the documented inventory and the actual inventory by location and units	%
Picking accuracy	Accuracy of the order picking process	# of errors per project
High priority ratio	The number of high priority order lines per total number of order lines	# of order lines
Perfect orders	Percentage of orders delivered to the production without missing materials or high priority orders	%
Inventory cost	The average monetary value of the material present in the warehouse	Cost in euros
Order processing cost	The total cost of the labor required for the project	Cost in euros
Labor cost	The cost of the labor needed for the activity	Cost in euros
Inventory space utilization	The rate of space occupied by storage	%
Picking productivity	The number of picks per labor hour	# per labor hour
Throughput (inbound)	The number of materials received and put away per hour	# materials per hour
Throughput (outbound)	The number of materials picked and delivered per hour	# materials per hour
Labor productivity	The ratio of the total number of store/pick activities per labor hour	# cycles per hour
Warehouse utilization	Average amount of warehouse capacity used over time	%
Purchasing productivity	The total number of purchasing lines per order	# of lines
Rework rate	The amount of rework needed per order	# of rework actions
Backorder rate	The number of backorders per project	# of backorders
Material retour rate	The number of materials going back to the warehouse per order	# of materials
Error rate (installed base)	The number of errors on the install base	# of errors
High priority ratio	The number of high priority order lines per total order	%
Lead time	The time production must wait for the supply of materials from the warehouse	Time in hours
Material availability	The amount of missing materials from a production order	# of materials

Appendix E Inventory Classification

Material nr	Material description	module	type	Supplier	# modules	# inkoop orders	# productie orders	verschil	Aantal ontvangst dagen	Aantal ontvangst weken	te besparen leverdagen	min order quantity	max order quantity	average order quantity	unique prices	avg price	Avg value per order	total value orders	Week met meer dan 1 levering	
000-1005	Bearing 6007-2RSR ø35	meerdere	M	DUURSMA INDUSTRIETECHNIEK	3	31	31	0	18	15	3	2	24	8,83	1	€ 4,86	€ 42,93	1545,48	ja	B
000-1010	Bearing SEB-F ø20 32x5/10/20/32	V600 Base (cabin)	M	BOSCH REXROTH B.V.	1	25	25	0	20	15	5	1	3	2,03	5	€ 226,82	€ 461,21	13844,07	ja	B
000-1029	Geared motor HA42 + T80B4 0,75kW	meerdere	M	UNIDRIVE B.V.	2	30	36	6	14	14	0	1	5	1,89	1	€ 138,00	€ 261,08	9660	nee	B
000-1053	Spindle nut FEM-E-S 32x10	V600 Base (cabin)	M	BOSCH REXROTH B.V.	1	18	18	0	15	11	4	1	4	2,59	4	€ 136,78	€ 354,39	7810,45	ja	B
000-1054	Spindle nut FEM-E-C 32x20	V600 Base (cabin)	M	BOSCH REXROTH B.V.	1	23	23	0	19	15	4	1	2	1,48	6	€ 144,75	€ 214,44	5793,25	ja	B
000-1063	Photocell WL12L-2B530	meerdere	E	SICK B.V.	2	44	47	3	26	18	8	1	5	2,24	2	€ 237,95	€ 532,15	29643	ja	B
000-1074	Proximity sensor E2A-M12KS04-M1-B1	Plasma straight	E	VAN EGMOND ELEKTROGROOTHA	1	54	51	-3	30	21	9	1	6	2,07	2	€ 16,13	€ 33,43	1778,4	ja	C
000-1075	Proximity sensor E2A-M18LS08-M1-B1	meerdere	E	VAN EGMOND ELEKTROGROOTHA	3	67	57	-10	35	22	13	1	4	1,64	3	€ 42,03	€ 68,98	2368	ja	C
000-1113	Sensor cable 4P-M12SF-1000-OPEN	meerdere	E	VAN EGMOND ELEKTROGROOTHA	4	89	86	-3	31	19	12	1	7	1,87	11	€ 10,23	€ 19,10	765,74	ja	C
000-1518	Roller runner block FLS 35H 0,08C	V600 Base (cabin)	M	BOSCH REXROTH B.V.	1	23	23	0	21	16	5	2	24	15,58	3	€ 7,63	€ 118,88	30654,14	ja	B
000-1521	Mounting bracket Y92E-B18	meerdere	E	VAN EGMOND ELEKTROGROOTHA	2	94	92	-2	42	22	20	1	8	4,03	9	€ 6,99	€ 28,17	1113,9	ja	C
000-1524	Plastic enclosure M22-IY1	V600 Base (cabin)	E	VAN EGMOND ELEKTROGROOTHA	1	8	8	0	8	8	0	1	2	1,33	3	€ 23,17	€ 30,89	85,44	nee	B
000-1566	Geared belt pulley TB 64-8M-50 - 2517	V600 Base (cabin)	M	KÖBO NEDERLAND B.V.	1	25	25	0	18	14	4	1	2	1,56	4	€ 5,37	€ 8,38	3283,8	ja	B
000-1676	Geared belt opt Omega HP 920 8M 50	V600 Base (cabin)	M	KÖBO NEDERLAND B.V.	1	11	11	0	11	9	2	1	1	1,00	2	€ 411,62	€ 411,62	486,85	ja	B
000-2367	Mounting bracket 580.075.12	V808M Feederrolls type 2	M	IGUS GMBH	1	20	20	0	17	12	5	1	2	1,43	2	€ 0,07	€ 0,10	202,41	ja	B
000-2378	Connection fitting I-BVND-M253GT M25	meerdere	M	IGUS GMBH	3	7	7	0	6	6	0	1	2	1,71	4	€ 35,50	€ 60,86	17,45	nee	B
000-2420	Connection fitting I-BVOD-P299GT PG29	V808M Feederrolls type 2	M	IGUS GMBH	1	31	31	0	25	17	8	2	4	2,10	8	€ 3,63	€ 7,60	285,03	ja	C
000-2421	Connection fitting I-BVND-M329GT M32	V304 Plasma bevel	M	IGUS GMBH	1	4	4	0	4	4	0	2	4	3,00	1	€ 6,55	€ 19,65	23,16	nee	A
000-2422	Connection fitting I-BVND-M406GT M40	V304 Plasma bevel	M	IGUS GMBH	1	10	10	0	10	10	0	1	2	1,20	2	€ 28,79	€ 34,55	39,74	nee	B
000-2423	Holder nut I-BMN-M40 M40	V304 Plasma bevel	M	IGUS GMBH	1	10	10	0	10	10	0	1	2	1,20	3	€ 26,67	€ 32,00	12,02	nee	B
000-2460	Mounting bracket 117.015.12PZ	V600 Base (cabin)	M	IGUS GMBH	1	4	4	0	4	4	0	1	1	1,00	1	€ 1,43	€ 1,43	9,64	nee	A
000-2464	Cable chain R17.015.063.0 29 links	V600 Base (cabin)	M	IGUS GMBH	1	4	4	0	4	4	0	1	1	1,00	1	€ 71,68	€ 71,68	76,56	nee	A
000-2515	Holder nut I-BMN-M32 M32	V304 Plasma bevel	M	IGUS GMBH	1	4	4	0	4	4	0	2	4	3,00	1	€ 1,48	€ 4,44	5,7	nee	A
000-2534	Connection fitting I-BVOD-P213GT PG21	meerdere	M	IGUS GMBH	2	3	3	0	3	3	0	2	2	2,00	2	€ 38,16	€ 76,32	17,55	nee	A
000-2561	Bearing 6006-2RSR ø30	V808M Feederrolls type 2	M	DUURSMA INDUSTRIETECHNIEK	1	12	13	1	12	12	0	1	4	2,07	1	€ 2,63	€ 5,45	171,68	nee	B
000-2563	Bearing 6205-2RSR ø25	V600 Base (cabin)	M	DUURSMA INDUSTRIETECHNIEK	1	36	36	0	22	19	3	2	8	4,65	5	€ 8,49	€ 39,50	489,18	ja	C
000-2588	Bearing 6208-2RSR ø40	V600 Base (cabin)	M	DUURSMA INDUSTRIETECHNIEK	1	17	17	0	14	14	0	1	2	1,50	3	€ 7,29	€ 10,94	318	nee	B
000-2607	Bearing XFM-2023-21 ø20	V600 Base (cabin)	M	ELCEE STAAL B.V.	1	5	5	0	4	4	0	4	4	4,00	2	€ 7,28	€ 29,12	53,6	nee	A
000-2612	Bearing 6210-2RSR ø50	V600 Base (cabin)	M	DUURSMA INDUSTRIETECHNIEK	1	8	8	0	8	8	0	4	8	5,00	2	€ 39,03	€ 195,15	612,8	nee	B
000-2622	Bearing SL04-5014-PPC2 ø70	V808M Feederrolls type 2	M	DUURSMA INDUSTRIETECHNIEK	1	21	21	0	17	17	0	1	4	2,83	2	€ 7,19	€ 20,33	5382	nee	B
000-2626	Track roller LR5204-X-2Z ø20	V808M Feederrolls type 2	M	DUURSMA INDUSTRIETECHNIEK	1	14	14	0	12	12	0	3	16	7,63	6	€ 199,67	€ 1.522,50	2141,1	nee	B
000-2677	Bearing SEC-F Alu ø20 32x5/10/20/32	V600 Base (cabin)	M	BOSCH REXROTH B.V.	1	27	27	0	22	17	5	1	3	1,77	2	€ 3,10	€ 5,50	12485,13	ja	C
000-2678	Bearing 62307-2RSR ø35	meerdere	M	DUURSMA INDUSTRIETECHNIEK	3	80	86	6	31	22	9	1	80	7,27	10	€ 14,04	€ 102,11	2163,8	ja	C
000-2681	Track roller KR62-PP M24x1,5 ø24	V808M Feederrolls type 2	M	DUURSMA INDUSTRIETECHNIEK	1	11	11	0	11	11	0	1	2	1,92	4	€ 618,85	€ 1.186,13	945,99	nee	A
000-2763	Chain simplex 3/4" 55 links	meerdere	M	KÖBO NEDERLAND B.V.	2	19	19	0	14	12	2	1	5	3,68	3	€ 2,76	€ 10,18	265,3	ja	B
000-2785	Chain simplex 3/4" 47 links	meerdere	M	KÖBO NEDERLAND B.V.	2	5	5	0	5	4	1	2	2	2,00	1	€ 3,11	€ 6,22	32,5	ja	A
000-2792	Chain simplex 3/4" 41 links	meerdere	M	KÖBO NEDERLAND B.V.	2	5	5	0	5	4	1	2	2	2,00	1	€ 2,16	€ 4,32	28,4	ja	A
000-2800	Chain simplex 3/4" 73 links	meerdere	M	KÖBO NEDERLAND B.V.	2	6	6	0	6	5	1	1	2	1,83	2	€ 1,35	€ 2,48	55	ja	B
000-2931	Chain duplex 3/4" 85 links	meerdere	M	KÖBO NEDERLAND B.V.	2	5	5	0	5	4	1	2	2	2,00	2	€ 4,09	€ 8,18	131,9	ja	A
000-3065	Lock washer MB04	V808M Feederrolls type 2	M	DUURSMA INDUSTRIETECHNIEK	1	12	12	0	12	12	0	1	2	1,08	1	€ 0,33	€ 0,36	4,9	nee	B
000-3069	Lock washer MB08	V600 Base (cabin)	M	DUURSMA INDUSTRIETECHNIEK	1	27	26	-1	18	18	0	1	4	1,70	3	€ 2,53	€ 4,29	18,48	nee	B
000-3072	Locknut KM04 M20x1	V808M Feederrolls type 2	M	DUURSMA INDUSTRIETECHNIEK	1	12	12	0	12	12	0	1	2	1,08	1	€ 2,58	€ 2,78	33,88	nee	B

Figure E-1 Screenshot of the table with the buy parts.

Appendix F Simulation Model

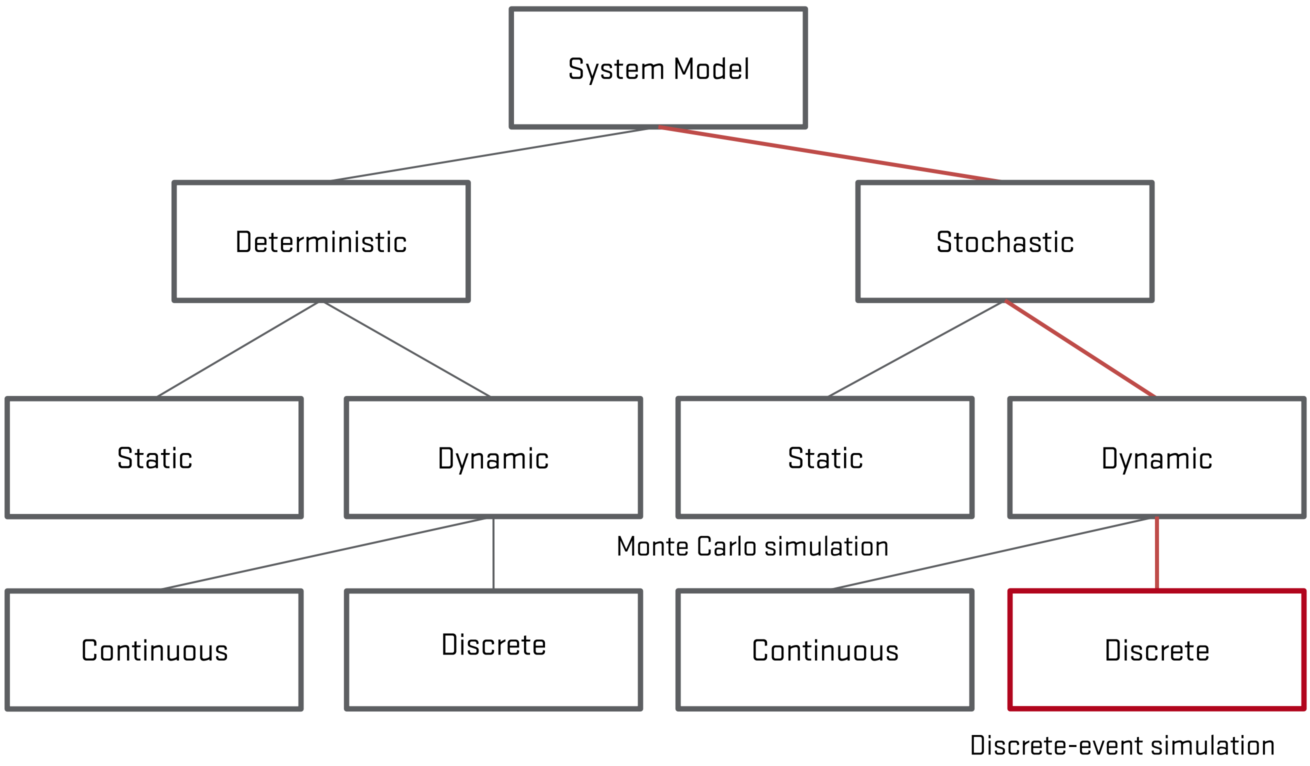


Figure F-1 Model taxonomy adapted from Law as quoted by Sawicki et al. (2016).

A discrete event simulation model consists of three basic elements: entities, attributes, and activities. An entity is any object involved with the model. Such an entity can have different characteristics or properties, called attributes. A moveable unit is a special type of entity, and can be moved between other objects. An activity is a process that generates a change in the state of the system. The state of the system is a set of variables that describe the behavior of the system (Sawicki et al., 2016). This section describes the general working of the simulation model of VSM.

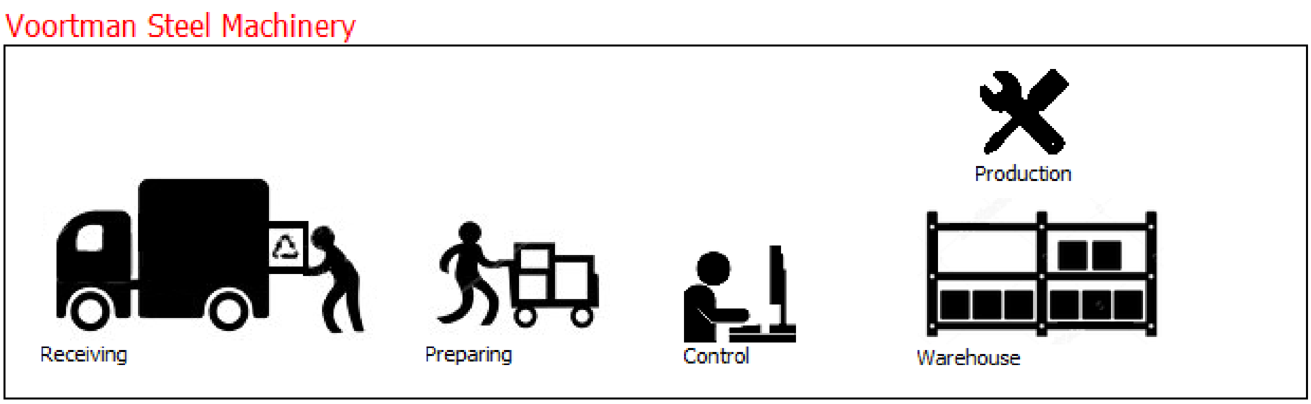


Figure F-2 Screenshot of the model of VSM with the different operation steps.

Flow of goods

Figure F-2 shows a screenshot of the simulation model. Each icon represents a frame, which is nothing more than a small piece of model. The flow of goods described in Chapter 2 is split in separate processes, taking place in separate 'frames'. In the receiving frame, suppliers deliver their goods. These goods are stored in a buffer in the Preparing frame. In the preparing frame, the received packages are unpacked and prepared for storage.

Unloading a truck is the first process in the model. We assume 30% of the deliveries is a parcel delivery. Parcel deliveries require no employee to unload the packages. The second process is the unpacking of the received packages. With this process, the individual materials are stored on a moveable table. We assume every package has one receipt to enter in the ERP system. The administration of the receipt takes place in the Control area. A moveable table filled with unpacked materials is transported to the store/pick location in the warehouse. At this location, the materials are stored in either the AS/RS or in the VLM. This decision depends on the settings of the model, based on the different scenarios we discuss in Section 5.4. In case of storage in the VLM, the materials are picked later, and then stored in a project pallet.

Figure F-3 shows a screenshot of the Warehouse Frame. The moveable tables containing the buy parts are moved with the icon named 'MoveTable'. Filled tables are placed at the location named 'Tafellocatie'. Materials picked from the VLM, the area in the upper right rectangle, are stored in the location called 'TafelPick'. The area in the upper left rectangle represents the AS/RS.

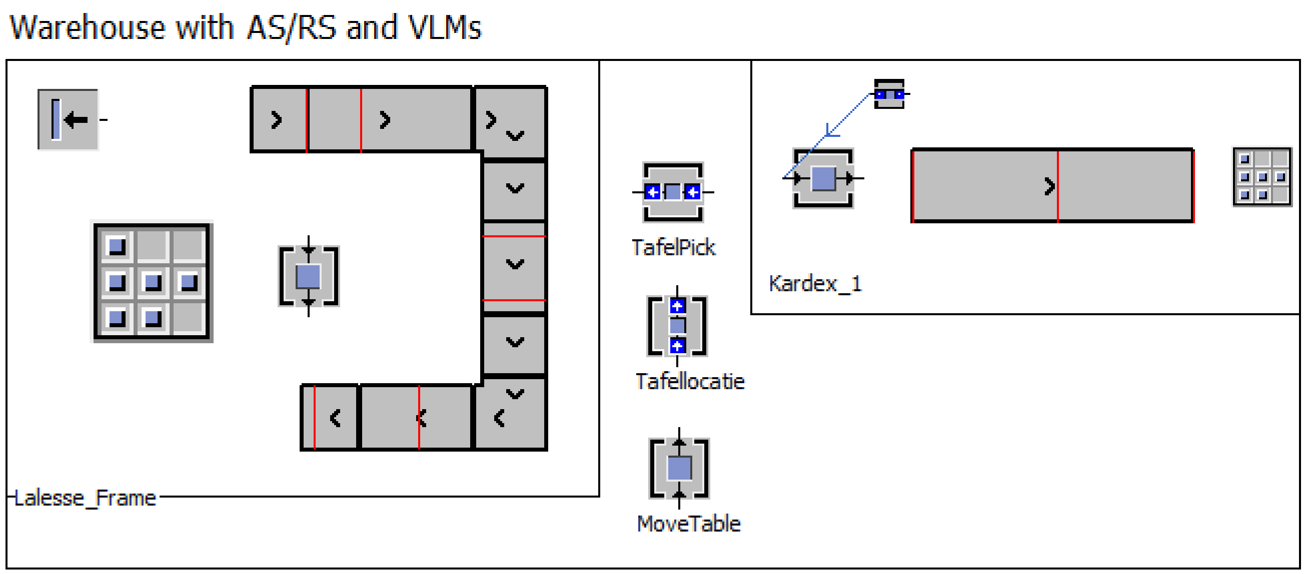


Figure F-3 Screenshot of the Warehouse Frame.

Figure F-4 shows a screenshot of the AS/RS at VSM modelled in Siemens Plant Simulation. The AS/RS is modelled based on the top view used in Figure 2-6. The icon in the middle, named 'Lalessecrane', represents the crane of AS/RS. Pallets are placed in the crane, and when the travel time is ended the pallet is placed on its destination. The big square on the left, named 'Lalesse', represents the 1337 available pallet storage locations. The I/O point is represented with the icon in the top left corner, named 'Production' as the pallets here leave the AS/RS towards the Production Department. The conveyor belts, called 'A' to 'K'. The black arrows indicate the transporting direction. The red lines over the conveyor belts are sensors, used for the pallet flow management. The blue lines have no special function, they only indicate these lines are paused now.

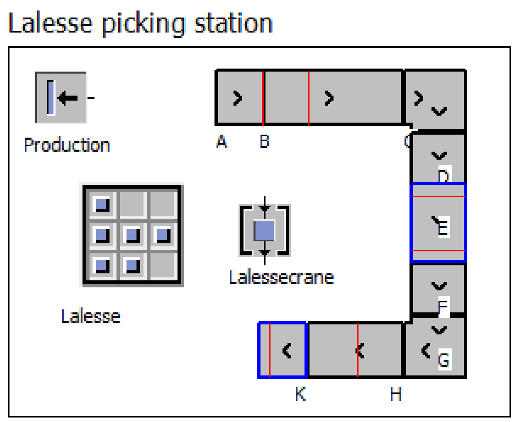


Figure F-4 Screenshot of the AS/RS Frame, representing the modelled version of the pick station at the AS/RS.

Figure F-5 shows a screenshot of the VLM at VSM modelled in Siemens Plant Simulation. The lift shaft of the VLM is represented with the big rectangle, named 'VerticalLift'. The lift itself is represented by the red rectangle with white borders. The travel time along the 'VerticalLift' is the sum of the time needed to take a tray in/out and to store/retrieve a tray. The vertical travel distance is not visually modelled, instead a tray waits the time needed for the vertical travel distance before it leaves the lift. The storage locations, the blue columns in Figure 2-8, are modelled with the icon called 'Kardex'. The I/O point can hold at most two trays and is modelled with the icons called 'Wachtrij' and 'PickStation'.

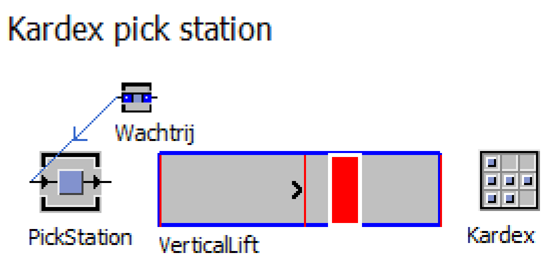


Figure F-5 Screenshot of the VLM Frame, representing the modelled version of the VLM and its pick station.

Number of replications

For every scenario and intervention, the minimal number of runs n for which the output values lie in a confidence interval of 95%, is calculated with the procedure explained in Section 6.1. Figure F-6 shows the calculation of the minimal value of n for Scenario 1. The output value used for the calculation is the average value of inventory per day. At $n = 20$, the estimated relative error $\delta(n\text{-}\alpha)/\bar{X}_n$, is smaller than the corrected target value γ'.

Experiment	Scenario1.0							
TestKPI	Inventory per day							
α	0.05							
γ	0.025							
γ'	0.02439							
Run	Ybar(i)	Xbar(n)	S^2 n	Tn-1,1-α /2	sqrt (S^2 n/n)	δ(n,α)	δ(n,α)/Xbar(n)	γ'-δ(n,α)/Xbar(n)
1	1444160	1444160						
2	1481240	1462700	#DIV/0!	12.70620474	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3	1457965	1461122	270860711	4.30265273	9501.942107	40883.6	0.027980934	-
4	1361190	1436139	4053234648	3.182446305	31832.50951	101305	0.07054001	-
5	1329193	1414750	5420347219	2.776445105	32925.20985	91415	0.064615701	-
6	1438168	1418653	4254634495	2.570581836	26629.03958	68452.1	0.048251503	-
7	1297749	1401381	5638715288	2.446911851	28381.87371	69447.9	0.049556796	-
8	1494744	1413051	6141626835	2.364624252	27707.46027	65517.7	0.046366141	-
9	1422477	1414099	5288298813	2.306004135	24240.23014	55898.1	0.03952912	-
10	1300567	1402745	5966179916	2.262157163	24425.76491	55254.9	0.039390555	-
11	1511632	1412644	6591240017	2.228138852	24478.63636	54541.8	0.038609722	-
12	1398091	1411431	5943933651	2.20098516	22255.96109	48985	0.034705929	-
13	1321585	1404520	6032456831	2.17881283	21541.4749	46934.8	0.033416993	-
14	1498295	1411218	6254681616	2.160368656	21136.76826	45663.2	0.032357297	-
15	1448114	1413678	5884602600	2.144786688	19806.73724	42481.2	0.030050141	-
16	1453397	1416161	5581293669	2.131449546	18677.01406	39809.1	0.028110594	-
17	1475544	1419654	5443679789	2.119905299	17894.59299	37934.8	0.026721195	-
18	1494609	1423818	5447581099	2.109815578	17396.64894	36703.7	0.025778383	-
19	1460662	1425757	5207528693	2.10092204	16555.37549	34781.6	0.024395148	-
20	1407147	1424827	4934501236	2.093024054	15707.48426	32876.1	0.023073786	succes
21	1286298	1418230	5620250960	2.085963447	16359.43147	34125.2	0.024061808	succes
22	1507214	1422275	5727363399	2.079613845	16134.89076	33554.3	0.023592027	succes
23	1415504	1421980	5456123493	2.073873068	15402.03755	31941.9	0.022462949	succes
24	1504349	1425412	5510366569	2.06865761	15152.51158	31345.4	0.02199038	succes
25	1435458	1425814	5275700522	2.063898562	14526.80353	29981.8	0.02102788	succes
26	1349038	1422861	5286989662	2.059538553	14259.93535	29368.9	0.020640725	succes
27	1346234	1420023	5296351655	2.055529439	14005.75497	28789.2	0.020273783	succes
28	1315530	1416291	5489892564	2.051830516	14002.41378	28730.6	0.020285785	succes
29	1378338	1414983	5335246538	2.048407142	13563.70224	27784	0.019635567	succes
30	1416011	1415017	5144849865	2.045229642	13095.60978	26783.5	0.018928064	succes

Figure F-6 Screenshot of a calculation of the minimal number of runs n.

Appendix G Results

Table G-1 shows the detailed list of results from the executed experiments. The results shown are the averages over 20 replications. All performance indicators with a time dimension are gathered in seconds, but for readability purposes rounded down to minutes, hours, or days.

Table G-1 Detailed list of results of the different experiments.

KPI Experiment	1	1.1	1.2	2	2.1	3	3.1
Average number of deliveries per day	6.3	7.1	3.8	6.3	6.3	3.4	3.4
total number of order lines	± 4800	± 4800	± 4800	± 3500	± 3500	± 2000	± 2000
Average value of inventory per day	€ 1,415,017	€ 339,511	€ 1,385,498	€ 1,151,533	€ 1,150,750	€ 1,192,370	€ 1,188,954
Average number of pallet retrievals per pallet	3.2	2.4	3.3	1.3	1.3	1.3	1.3
Average number of pallet retrievals per project	5.6	4.3	5.7	3.1	2.9	3.0	3.0
Average number of pallets used per project	1.8	1.8	1.7	2.3	2.2	2.3	2.2
Average number of pallet movements per day	23.5	14.3	23.2	9.9	9.4	9.6	9.5
Average number of VLM store/pick cycles per day	0	0	0	15.2	18.2	13.4	14.7
Average time spent in warehouse per material in days	11.25	3.9	11.25	14.6	14.2	18.8	19.2
Average working time per day in hours	4.7	4.5	3.8	4.3	4.2	2.5	2.5
Average unloading time per day in minutes	43	49	27	44	44	24	24
Average unpacking time per day in minutes	109	104	92	91	90	49	49
Average administration time per day in minutes	101	97	85	84	84	45	46
Average store/pick time per day in minutes	26	18	26	39	36	30	28

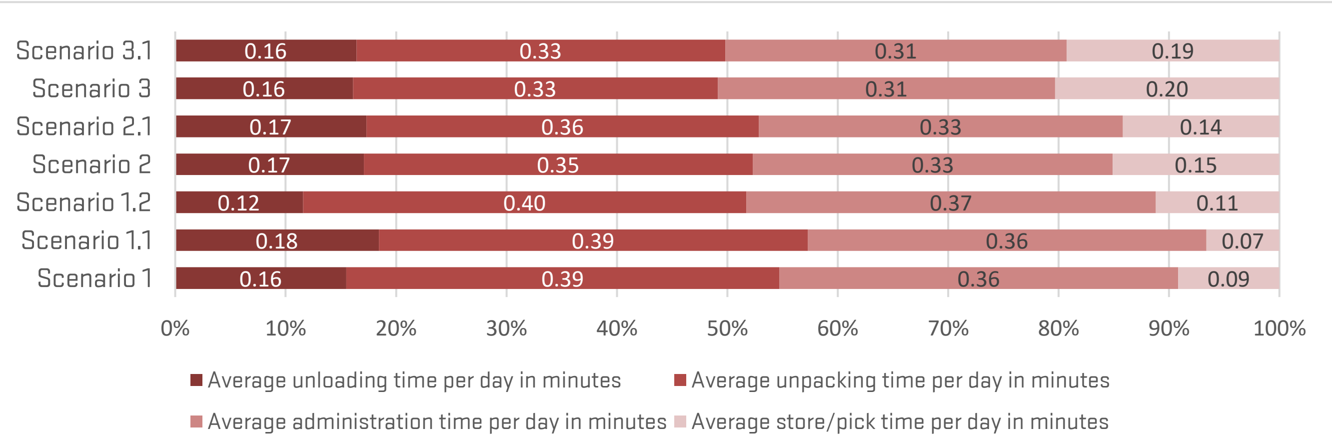


Figure G-1 Overview of the division of work per task per day per experiment.

Confidence intervals

F	G	H	I	J
pallet movements per day				
4	6		Wj	Wj - Wbar ^2
10.4909	9.62727		0.86	0.34
10.1091	9.62727		0.48	0.04
9.72727	9.72727		0.00	0.08
9.90909	9.79091		0.12	0.03
9.98182	9.50909		0.47	0.04
10.1091	9.79091		0.32	0.00
9.90909	9.91818		-0.01	0.08
9.87273	9.73636		0.14	0.02
9.8	9.49091		0.31	0.00
9.79091	9.7		0.09	0.04
9.8	9.54545		0.25	0.00
9.57273	9.57273		0.00	0.08
9.89091	9.87273		0.02	0.07
9.74545	9.40909		0.34	0.00
9.68182	9.48182		0.20	0.01
9.9	9.65455		0.25	0.00
9.89091	9.6		0.29	0.00
10.1818	9.59091		0.59	0.10
9.94545	9.70909		0.24	0.00
9.76364	9.65455		0.11	0.03
9.98182	9.43636		0.55	0.07
9.88182	9.6		0.28	0.00
9.78182	9.62727		0.15	0.02
10.0909	9.68182		0.41	0.02
9.73636	9.68182		0.05	0.05
10.0364	9.48182		0.55	0.08
9.95455	9.78182		0.17	0.01
9.93636	9.80909		0.13	0.02
9.92727	9.54545		0.38	0.01
10.1545	9.53636		0.62	0.12
		Sum	8.36	1.34
	Weighted average, Wbar		0.279	
		Var Wbar	0.00	

L	M
Confidence interval	
Lower	Upper
0.186009308	0.37157
T-Test	8.1E-08
yes	
Signicant difference	

Figure G-2 Screenshot of a calculation for significance between the outputs of two experiments.

Table G-2 Confidence Interval for the number of pallet retrievals per project between Scenario 1 and Intervention 1.1.

Confidence interval	
Lower	**Upper**
2.483388	2.596345
T-Test	3.86E-39

Table G-3 Confidence Interval for the number of store/pick cycles in the AS/RS per day between Scenario's 2 and 3.

Confidence interval	
Lower	**Upper**
0.186009	0.371566
T-Test	8.15E-08

Table G-4 Comparison of the different storage strategies.

Storage strategy	Project based	Anonymous – First Fit		Anonymous – OOS	
Output per experiment	Scenario 1	Scenario 2	Scenario 3	Intervention 2.1	Intervention 3.1
Average number of pallets per project	1.8	2.3	2.3	2.2	2.2
Average number of pallet retrievals per project	5.6	1.3	1.3	1.3	1.3
Average store/pick time per day in minutes	26	39	30	36	28
Average working time per day in hours	4.7	4.3	2.5	4.2	2.5