Master's Thesis

Coping with Variability: Improving the Inbound Process of the VMI Holland Warehouse

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Management summary

VMI Group is a manufacturing company that is specialized and market leader in the manufacturing of production machines for the tire, rubber, can, and care industry. The warehouse department of the company, where this research is performed, is responsible for the delivery of materials to the manufacturing department. Late or incomplete deliveries by the warehouse can result in delays in manufacturing, idle project teams, rescheduling of projects, and it endangers sales. VMI Holland has limited insight into the performance of the warehouse processes. For the inbound activities, it is hard to control the workload during the day due to the variability in arrival times of suppliers and the discrepancy between the number of expected and actual delivery items. This variability causes insufficient and an excess of capacity. Insufficient capacities results in additional costs of overtime. An excess in capacity causes inefficient processes.

The objective of this research is to provide the management with improvements on the current warehouse processes in order to control the variation in workload and to improve process efficiency. The main question for this research is:
"*What is the current performance of the logistic processes of the VMI Holland warehouse, and how can we control and improve the efficiency and effectiveness of the internal processes, while maintaining or improving the quality of outbound?"*

With the help of a literature study, we created a list of performance indicators that are commonly used in a warehouse environment. The list includes indicators that describe the utilization, productivity, and effectiveness of processes at the operational, tactical, and strategic level. After discussing the indicators with the main stakeholders of the VMI Holland warehouse, we selected the following 14 indicators:

- Storage utilization;
- Queueing time of processes;
- Queueing length of processes;
- Workforce flexibility;
- Throughput;
- Dock to stock time;
- Receiving time;
- Put away time;
- Order lead time;
- Storage accuracy;
- Order picking time;
- Shipping time;
- Shipping accuracy;
- On-time delivery.

We customized the performance indicators to the VMI Holland warehouse and provided them with a description, the measurement method, the formula, the norm, a description of how to measure, how often, and how to react on the performance. We put the selected indicators into a framework: '*The Performance wareHouse of VMI Holland',* shown in Figure 1. This framework gives a clear overview of the performance of the warehouse and enables the foremen and management to control the performance of the processes.

To find potential improvements on the system, we built a simulation model with Siemens Plant Simulation. We focused on the inbound processes of the warehouse, because of the presence of high variability in the workload. To model variability, we determined the theoretical distribution functions of workstations, properties of material types, arrival times, and the planned workforce.

We examined two scenarios, with several interventions. The first scenario represents the current situation of the warehouse inbound process, where we try to find potential improvements under historical settings. The second scenario represents a future situation, where the company faces an increased material flow to identify bottlenecks in the process. We designed the following scenarios and interventions:

- Scenario I: the current situation of the warehouse inbound process;
  - Intervention 1: a flexible workforce, to reduce variation in workload;
  - Intervention 2: all items arrive at the start of the day, to reduce arrival variation.
- Scenario II: a future situation of the warehouse inbound process, representing an increased material flow with a factor 2;
  - Intervention 1: expanding maximum capacities of bottleneck workstations by a stepwise approach;
  - Intervention 2: eliminate the material flow from anonymous warehouse;
  - Intervention 3: all items arrive at the start of the day, to reduce arrival variation.

Each simulation experiment runs for 83 days and consist of 13 replications. The outcome of the simulation provides information on the dock to stock time of items, average waiting times of processes, and the occupation rates of workstations.

Results

The actual results of the simulation are not available in the public version of this report. We do give the main findings.

Scenario I: current warehouse situation

- The results of scenario I are not available in the public version of this report.

Interventions of scenario I

- A flexible workforce improves the performance of the system. The performance improvement is a result of a more efficient distribution of the workload over the planned workforce;
- When all items arrive at the start of the day, the company needs an unrealistic large buffer in front of the receive stage. The workload during working hours of the receive station increased with 9%, resulting in a reduction in overtime.

Scenario II: increased material flow

- The results of scenario II are not available in the public version of this report.

Interventions of scenario II

- To ensure 99% of the items have a dock to stock time within 8 hours, there is a need to increase the maximum capacities of:
  - The accept workstation for RB/EP items from 11 to 13 employees;
  - The put away workstation for RB items from 4 to 6 employees;
  - The put away workstation for EP items from 3 to 5 employees.
- Without a material flow from the anonymous warehouse, the average dock to stock time is improved. There is still a need for an investment in the maximum capacity of the accept station for RB/EP items;
- When all items arrive at the start of the day, the total average dock to stock time increases. The workload during working hours of the receive station increased with 8%, resulting in a reduction in overtime.

VMI Holland can improve its performances by designing a flexible workforce together with the implementation of the proposed framework of performance indicators to deal with the variability of the workload. This improvement ensures that items are placed within 8 hours into their storage locations, preventing expensive delays at the manufacturing department. In addition, the framework enables the company to control its processes and make decisions at the strategic, tactical, and operational level. When the material inbound increases, there is a need to invest in the capacities. We propose a roadmap in Table 1 to successfully implement process improvements at the VMI Holland warehouse.

Table 1: Roadmap to process improvement.

Steps	Responsible	weeks
Step 1: Implement performance framework		**10**
1.1 Perform system adjustments for data collection	IT department	6
1.2 Construct queries to measure indicators	IT department	4
Step 2: Design a flexible workforce		**8**
2.1 Define recommended competences of workstations	Foremen	2
2.2 Documentation of employees competences	Foremen/Randstad	2
2.3 Train employees	Foremen	4
Step 3: Increase capacities of workstations		**7**
3.1 Increase capacity put away station RB items	Supply innovator	5
3.2 Increase capacity put away station EP items	Supply innovator	5
3.3 Increase capacity accept workstation RB/EP items	Supply innovator	5
3.4 Modify/simplify workstations to prevent setup times	Foremen	2
Step 4: Monitor the performance of the processes	Foremen / management	**continuously**

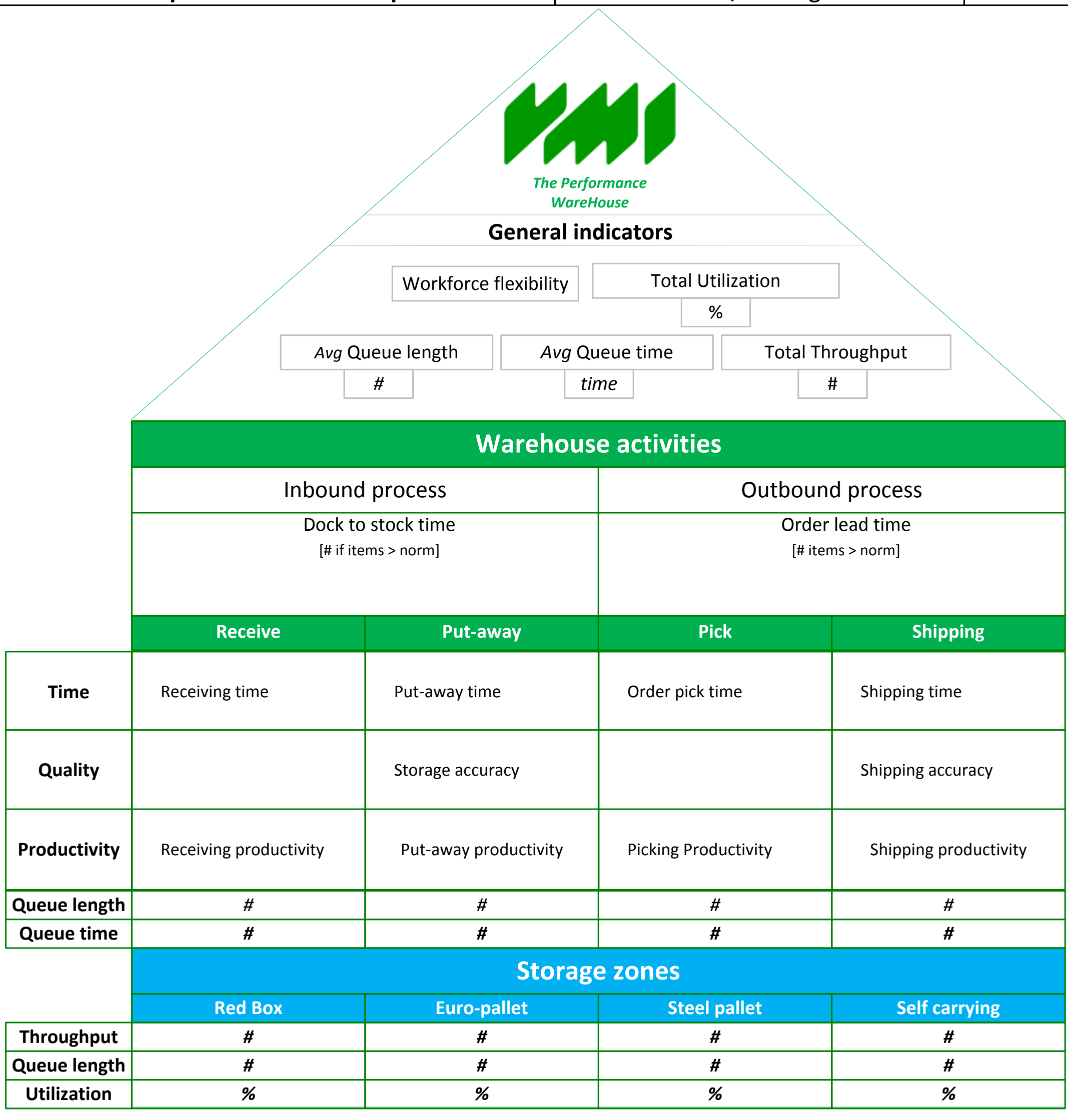

Figure 1: The Performance wareHouse of VMI Holland.

Preface

This report is written to conclude the master Industrial Engineering and Management at the University of Twente. Within this master program, I followed the Production and Logistics specialisation track. This research, at the warehouse department of VMI Holland, was a perfect opportunity to put my knowledge into practice. I really enjoyed my time investigating the warehouse processes, performing data analysis, and designing a sound simulation model.

I thank my supervisor at VMI Holland, Berry Mennink, for giving me the opportunity to let me perform this research. I also want to thank the people from VMI Holland for their support during this research, especially Berthold Gerrits and Erik Uijttenboogaart for the valuable discussion sessions and their critical feedback.

I am grateful to my supervisors from University Twente, Peter Schuur and Martijn Mes. The feedback sessions once a month were very helpful and gave valuable insight in order to improve my research.

Finally, I would thank my girlfriend, family, and classmates for their support during my research.

I hope you all enjoy reading this report and I hope this research will help VMI Holland to remain a prominent and healthy company.

“After twenty years of education, starting at an age of 4, I am ready to enter the labour market and start with a new period in my life.”

Bob Brummelhuis
Vaassen, February 2016.

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1. Introduction to the problem

In the framework of completing the master study Industrial Engineering and Management at the University of Twente, we conduct research at the VMI Group. In this chapter, we give an introduction to the research problem. In Section 1.1, we give a description of the VMI Group and in what market the company is operating. Section 1.2 shows the organisational chart of the company and clarifies the department the research thesis is performed. In Section 1.3, we give the context of the problems. In Section 1.4, the research goal and objectives are set. In Section 1.5, we formulate the boundaries of the research. Finally, in Section 1.6, we give the research question and methodology that we need to solve the research problem.

1.1 Company description

VMI Group is a manufacturing company founded after the end of the 2nd World War. The company was specialized in repair and small construction work at the Dutch Railways. In the early 1960s, VMI Group entered the rubber and tire industry. Nowadays, the company is market leader in production machinery specialised in the manufacturing of machines for the tire, can, rubber, and care industry. The success of VMI Group lies in the constant effort to develop new innovative products and solutions to meet current and future manufacturing demands. The company strives for "operational excellence in all its services with the dedicated objective of providing genuine added value to its global customer base". VMI Group focuses on maintaining ongoing growth and a healthy profit. The company's common stock is 100% owned by TKH Group N.V. at Haaksbergen. TKH Group is an internationally operating group of companies specialized in creating and supplying innovative telecom, building and industrial solutions. In 2014, the TKH Group had a turnover of 1.35 billion and VMI Group had a turnover of XX million euro's. In 2015, the company aims to achieve a turnover of XX million.

VMI Group employs around 1200 employees and operates in the Netherlands, Germany, USA, China, and Brazil. The European headquarters of VMI Group is located in Epe, the Netherlands, with 800 employees. At the headquarters of VMI Group, the specialized machines are made with a high R&D content. Figure 1.1 shows two examples of products: a MAXX® tyre assembly machine on the left, and an ACE-500 cotton machine on the right.

Figure 1.1: Examples of products of VMI Group

1.2 Company structure

In the first part of this section, we give the organisational structure of the TKH Group. In the second part, we give the organigram of VMI Group and clarify where the research is performed.

1.2.1 TKH Group

TKH Group aims to be an innovative leading technology (niche) player that, by means of combinations of its core technologies, offers total solutions that relieve any concerns of customers and lead to greater efficiency, more comfort, and improved safety. At the end of 2012, TKH Group made the choice to specifically gear its growth ambitions to seven vertical growth markets: *tunnels and infra, care, fibre optics networks, parking, marine, oils & gas, tyre building,* and *machine vision.* The organisational structure of the TKH Group is given in Figure 1.2. Along with five other companies that produce manufacturing systems, they are responsible for 32.7% of the total turnover of the entire TKH Group.

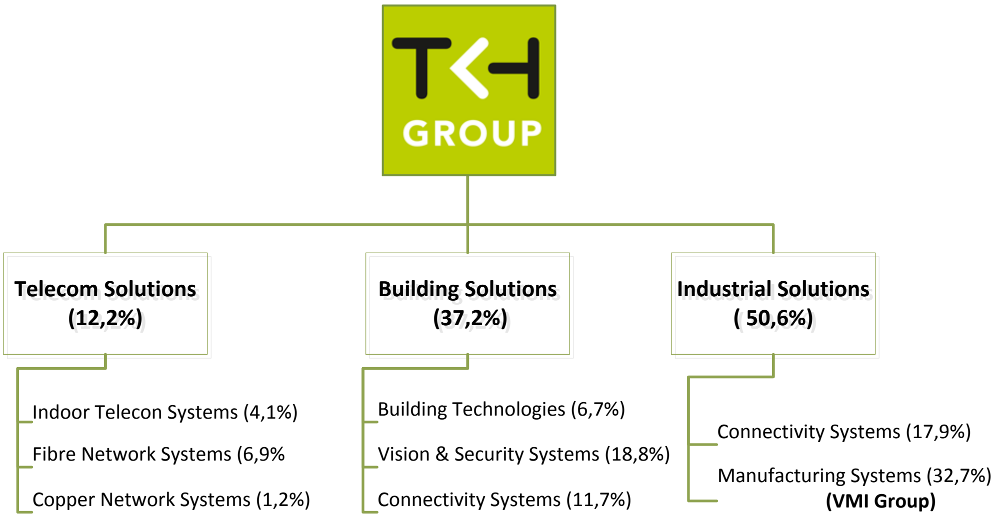

Figure 1.2: Organisational structure of TKH Group NV and the fragment of the total turnover. (Annual report, 2014)

VMI Group consists of six divisions: VMI *Holland,* VMI *America,* VMI *Ltd,* VMI *Yantai,* VMI-*AZ,* and VMI *South America*. We perform the research for VMI Holland, the headquarters of the VMI Group. In the next section, we clarify the organigram of VMI Holland.

1.2.2 Organigram VMI Holland

Within VMI Holland, we perform the research at the warehouse department located at Vaassen supervised by the head of material management. In Figure 1.3, we see that the warehouse department is part of the logistic department that is controlled by the Chief Operating Officer.

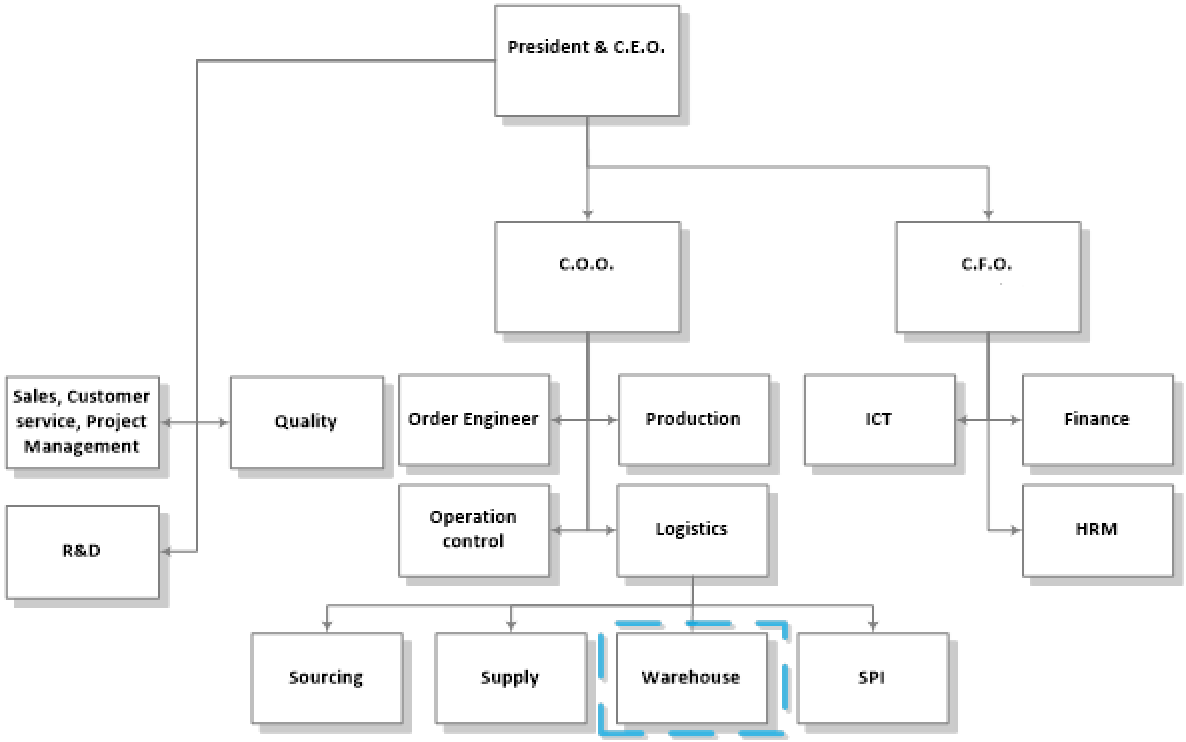

Figure 1.3: Organigram of VMI Group

1.3 Context of the problem

VMI Holland manufactures specialised production machineries, which are built in phases, each consisting of several modules. Each module is separated into production orders that contains a set of articles and a drawing. A mechanic is responsible for the assembly of the production order.

The main task of the VMI Holland warehouse is to compose production orders that consist of materials needed at the manufacturing department. To prevent downtime at the manufacturing department, it is important that a production order does not contain wrong items or missing items. When items are missing the mechanics cannot complete their modules, which causes a delay in the project.

VMI Holland makes a distinction between project-based items and non-project-based items. Besides exceptions, non-project based items, also called anonymous items, are commonly used, cheap and have a high demand. Also products with a long lead time or products that cannot be delivered in the right quantity are anonymous items. These items are stored at a smaller warehouse located at Epe. Project-based items are less frequently used and expensive to keep on stock, and are therefore purchased per production order. Project-based items are procured Just-In-Time and stored at the central warehouse at Vaassen. At the central warehouse, items are put-away into storage locations, where each of these locations is allocated to a single project/production order. Anonymous items can become project-based when they get assigned to a project. In that case, these items move to the central warehouse and are put-away in the associated project location.

The head of material management, responsible for the warehouse of VMI Holland, wants to achieve a delivery of production orders without any errors, executed in a cost efficient way. This is translated into three goals: "*(i) a high quality of warehouse outbound, (ii) a high efficiency and effectiveness of the production facilities, and (iii) a high throughput of articles.*"

VMI Holland wants to improve the quality of the output of the warehouse. Wrong or missing articles lead to delays at the production facility. Solving these errors is time consuming and induces additional costs.

Currently, there is a variation in deliveries of items by suppliers during a day that causes variations in the workload distribution of the warehouse activities. Currently, there is limited insight into the effects of this variation. VMI Holland wants insight into the effects of this variation of the performances of the warehouse processes.

VMI Holland wants to achieve Just-In-Time delivery for the both storage and production facilities. The company wants to know if the current processing time of items can be reduced. According to VMI Holland, from the moment items arrive at the warehouse it takes 6 working days to store and pick these items. When items arrive too early, storage locations are unnecessarily occupied, which demands additional storage space.

In addition, the company expects an increase in product sales resulting in a higher material flow through the warehouse. There is no insight whether the processes of the warehouse can handle this amount of material. Therefore, there is a need to analyse the current warehouse processes with an increased material flow and come with potential improvements.

Table 1.1 gives an overview of problems from important problem owners.

Table 1.1: Overview of problem owners and their problems.

Problem owner	Problem
Confidential	

1.4 Research Goal

The goal of this research is to provide the management of VMI Holland with improvements on the current warehouse processes in order to decrease the variability in workload and to improve process efficiency. The research improves the understanding of how the processes are operated and determines potential targets for process improvement.

To find and analyse potential improvements, we design a simulation model to simulate the material flow through the warehouse processes. With a simulation model, we can predict how processes behave under different scenarios and interventions, and what improvements should be implemented to reach a given performance standard.

To analyse the performances of the processes in the current situation and the outcomes of the simulation interventions and scenarios, there is a need to create a list of performance indicators.

Objectives of the research:

- Provide VMI Holland with a list of performance indicators that enables the company to measure its (current) performance of the warehouse processes and enables us to analyse the outcomes of simulation runs;
- Create and execute a simulation model that gives a visual representation of the warehouse processes and provide us with outcomes from different scenarios and interventions;
- Provide VMI Holland with suggestions for improvements on the warehouse activities, so that the variation in workload can be decreased and the efficiency of processes being increased;
- Give the company advice on how the simulation model can be improved in order to increase the reliability and validity of the outcomes of the model.

1.5 Research Scope

The research focuses on the resource capacity planning of the main warehouse processes at the central warehouse of VMI Holland. This managerial area addresses the dimensioning, planning, scheduling, and control of renewable resources that includes equipment, facilities, and staff (Hans, Van Houdenhoven, & Hulshof, 2012).

The boundaries that we take into account are as follows:

- We cannot influence the arrival time of the delivery of items by suppliers. The goal of the research is to control this variation, not to influence it;
- We only take the processes of the central warehouse, located in Vaassen, into account and exclude the 'anonymous warehouse' processes from the research. We do take its material flow to the central warehouse into account;
- We cannot influence the dimensions and weights of the items that arrive at the warehouse;
- We cannot influence the needs of the production facility: we do not change the output of the warehouse;
- The dimensions of the current warehouse are set and cannot be changed;
- The warehouse must remain flexible. If necessary, the warehouse must adapt to increases and decreases the inbound and outbound of the material flow;
- The management team of VMI Holland desires a portable warehouse in terms of the movement to other building sites. Therefore, there is no need for improvements in automatic storage systems.

1.6 Research question and methodology

To give a solution to the problem and to realise the research goals, we formulate the following main question:

What is the current performance of the logistic processes of the VMI Holland warehouse, and how can we control and improve the efficiency and effectiveness of the internal processes, while maintaining or improving the quality of outbound?

In order to measure the current performance of the logistic processes of the VMI Holland warehouse, we seek for performance measurements in the literature and apply them to the VMI Holland warehouse. With performance measurement, the head of material management and the foremen are able to control and improve the performance of the logistic processes. To define relevant indicators, we study the literature regarding the definition of a warehouse and its activities. After we found relevant indicators, we perform a stakeholder's analysis to make a selection of indicators and set standards for VMI Holland. To gain insight into the current performance, for which currently limited data is available, we design a computer simulation model. With this model, we analyse two scenarios: a scenario that simulates the current settings of the warehouse and a scenario that simulates an increased material flow. For each scenario, we study several interventions to identify potential process improvements, analyse the outcomes, and perform new interventions to find further improvements.

The processes within the warehouse system are interconnected and subject to both variability and complexity. It is difficult to predict the performance of systems that are subject to any one of variability, interconnectedness, and complexity (Robinson, 2004). Simulation models are able to represent the variability, interconnectedness, and complexity of a system. With a simulation model it is possible to predict system performance, compare alternatives, and determine the effects of these alternatives on system performance. In Section 5.1, we give an extended explanation why we use a simulation model to analyse the system.

To structure this research and create a sound simulation model, we modify the *steps to a simulation study* proposed by Law (2007). Figure 1.4 gives an overview of the research approach with references to sections in this report.

To answer the main question in a systematic way, we formulate a set of sub questions. For each sub question, we describe the purpose of the question and give the research methodology to answer this question.

In the first sub question, we describe the current situation and collect information on the system structure and operating procedures of the VMI Holland warehouse. To get a better understanding of the processes, we participate in all the company's processes that take part or influence the warehouse processes. To gather relevant information, interviews will be taken with all internal stakeholders that involve or influence the warehouse processes. We use available data from the ERP system to determine the characteristics of the material flow. We also examine the current indicators VMI Holland uses to measure its warehouse performances. We answer sub question 1 in Chapter 2.

Question 1: *What are the characteristics and parameters of the processes of the VMI Holland warehouse?*

In the second sub question, we perform a literature study to find performance indicators and metrics that are commonly used for performance measurement in the warehouse environment. We seek for indicators at the strategic, tactical, and operational level. First, we study the definition of the warehouse function and identify the characteristics of the main activities of a warehouse. Then, we make use of reliable literature sources such as: Scopus, Web of Science, Science Direct, and Google Scholar to qualify and select indicators based on the age of the article and the number of times cited. We examine the references of the articles to find new sources of theory. We answer sub question 2 in Chapter 3.

Question 2: *What are the performance indicators of general warehouse processes?*

In the third sub question, we make a selection of the performance indicators found in the previous sub question that fit the needs of the stakeholders of

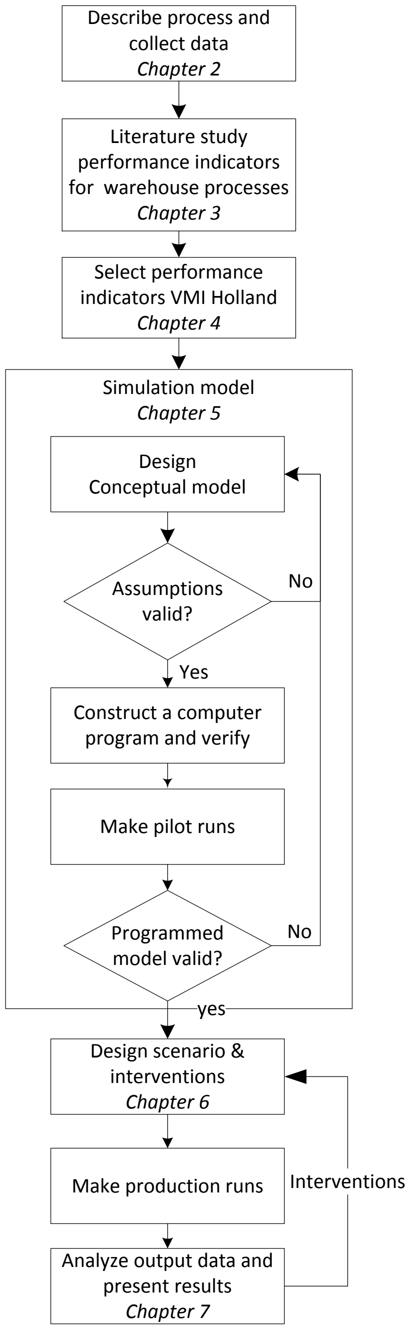

Figure 1.4: Research design.

the company. We adapt the indicators to the VMI Holland warehouse processes and discuss them with important stakeholders to set deliberately standards. The result is a set of indicators that enables the company to control the warehouse performance at the strategic, tactical, and operational level. We answer sub question 3 in Chapter 4.

Question 3: *What performance indicators fit the needs of the stakeholders of the VMI Holland warehouse?*

In the fourth sub question, we create a simulation model to analyse the inbound process of the VMI Holland warehouse. To make a sound simulation model, we construct a conceptual model that describes the objectives, inputs, outputs, content, and assumptions and simplifications of the simulation model. Thereafter, we determine the number of replications we need to run to get a reliable outcome, build the model with Siemens Plant Simulation, and verify and validate this model. The result is a simulation model that represents the inbound processes of the warehouse. This model enables us to run scenarios and interventions to find potential improvements on the system. We answer sub question 4 in Chapter 5.

Question 4: *What does the simulation model of the VMI Holland warehouse look like?*

In the fifth sub question, we design scenarios and interventions of the warehouse processes that we simulate to find potential improvements. In the first scenario, we seek for improvements in the current situation. In the second scenario, a future scenario, we seek for potential improvements when the company faces an increased material flow. For each scenario, we design several interventions that may lead to improvements. We answer sub question 5 in Chapter 6.

Question 5: *What are the scenarios and interventions for the simulation model of VMI Holland?*

In the sixth sub question, we analyse the outcomes of the scenarios and interventions to find potential improvements and make recommendations to improve the inbound process. We answer sub question 6 in Chapter 7.

Question 6: *How can VMI Holland improve their warehouse processes based on the results of experiments with various interventions and scenarios?*

In Chapter 8, we give the conclusion of the research and provide the company with potential improvements and give recommendations. We also discuss the limitations of the research and possibilities to further research.

2. Current situation

In this chapter, we describe the current situation of the VMI Holland warehouse. In Section 2.1, we give a brief description of the relation between the two different warehouses of VMI Holland, give an overview of the warehouse processes, and explain the core products of VMI Holland. In Section 2.2, we give a comprehensive description of warehouse processes, its characteristics, and the interconnected relations. Here, we analyse for each processes the work method, the processing time, and the maximum capacity. In Section 2.3, we describe the performance indicators VMI Holland currently uses to measure the performance of the warehouse. Finally, in Section 2.4, we give the conclusion. The layout of the VMI Holland warehouse is given in Appendix A.

2.1 Introduction to the VMI Holland Warehouse

The warehouse of VMI Holland holds raw materials and provides assembly kits that are needed by mechanics at the production facility. VMI Holland manufactures high-tech machines for which the customer order decoupling point lays between engineer-to-order (ETO) and make-to-order. The definition of ETO is given by Gelders (1991): *"In an engineer-to-order environment a company designs and produces products to customer order."* (Gelders, 1991). The high degree of specialization and revisions in the requirements of a machine by the customer makes it hard use inventory as a buffer for demand variation.

2.1.1 The central warehouse and the anonymous warehouse

VMI Holland makes a distinction in storage location based on two different inventory policies: project based inventory and non-project based inventory, called anonymous inventory. Anonymous items are ordered based on an *Economic Order Quantity* policy and are stored, in a different warehouse located at the production site, into fixed storage locations. This warehouse consists of products that are regularly used in production orders or by employees at the office. Project-based inventory is stored at the central warehouse location at Vaassen. In this warehouse, items are stored commonly to the production order they belong to.

A production order, the output of the central warehouse, consists of both anonymous and project-based articles. The items are brought together at the central warehouse and moved to the production site. Therefore, the anonymous articles move from one warehouse to another.

Currently, both project-based and anonymous items arrive at the warehouse location at Vaassen. Anonymous items are sorted out and transferred to Epe. Figure 2.1 gives a visualisation of the interaction between the two warehouses. As we can see in Figure 2.1, 12.5% of the items that are delivered by suppliers are received and accepted at the central warehouse, and move to the anonymous warehouse (arrow a). These items arrive as a package, containing the same article according to their *Economic Order Quantity.*

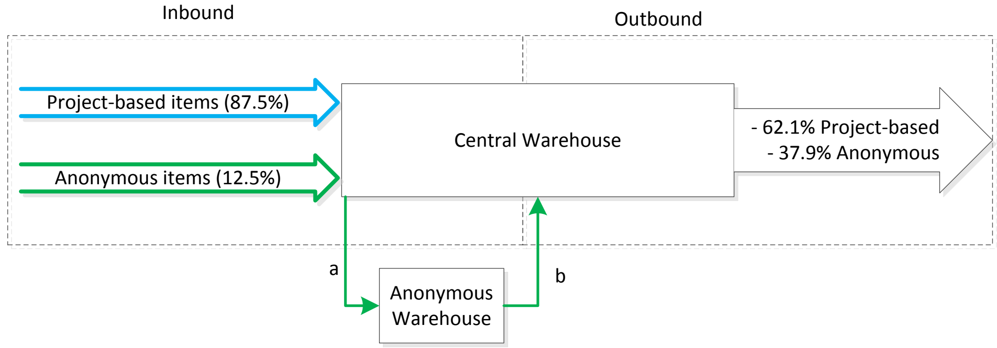

Figure 2.1: The inbound material flow of the central warehouse of VMI Holland (Source: Outbound report: week 1-2015 till week 26-2015)

The central warehouse consists of over 7,000 storage locations that can each hold several items. To keep inventory low, VMI Holland uses a Just-In-Time inventory strategy. In order to deliver the items just in time, it is of great importance that items move without delays through the warehouse processes. Inefficient warehouse processes demands expensive storage space.

As explained in Section 1.5, this thesis only focusses on the central warehouse, but takes the material flow from the anonymous articles into account.

2.1.2 The material flows of the central warehouse

Figure 2.2 gives an overview of the two different material flows through the central warehouse of VMI Holland. The dotted arrows represent the material flow that moves to the anonymous warehouse. The straight lines represent the material flow that end up at the manufacturing department.

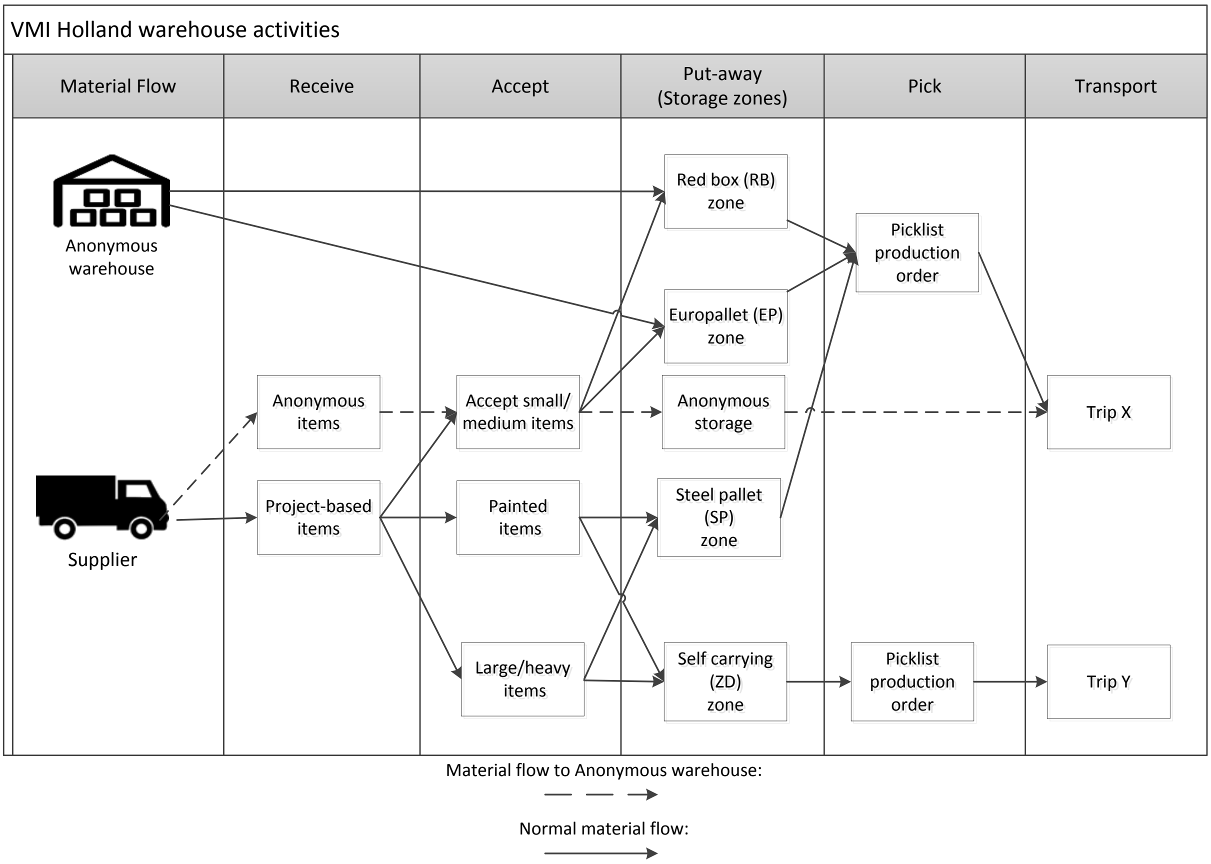

Figure 2.2: Overview of the warehouse activities of the VMI Holland warehouse

As we see in Figure 2.2, there are two material flows that determine the inbound material flow of the warehouse. All items are delivered at the VMI Holland central warehouse by a supplier. This supplier delivers both anonymous and project-based items. Project based articles pass all warehouse activities and wait to get picked. Anonymous items only pass the receiving and acceptance stage and move directly to the anonymous warehouse. When there is a need for these items in a production order, they move back to the central warehouse where they get stored with the rest of the production order items. Trip X transports consists of packages (production orders) that contain items that lie into red boxes, euro pallets, and steel pallets. Trip Y transports consists of large items.

Section 2.2 provides a comprehensive description of the warehouse activities and clarifies the characteristics of the material flows.

2.1.3 Type of products

In this section, we clarify what manufacturing machines are responsible for how many production orders and items that move through the warehouse. Table 2.1 gives an overview of the machines that are produced the last year and how many articles and production orders they are composed of.

Table 2.1: Master Production Schedule (week 40 2014 till week 40 2015, including WOP's (adjustments on project). *N* is the number of machines the calculation is based on.

Main product category	# of machines produced	# of order lines per machine through warehouse	# of production orders
Ace(300)	XX	XX	XX
Ace(500)	XX	XX	XX
BEADAPEX	XX	XX	XX
TBM's EXXIUM	XX	XX	XX
TBM's MAX	XX	XX	XX
TBM's VAST	XX	XX	XX
TBM's VMI24X	XX	XX	XX
Machine X	XX	XX	XX

As we see in the table, most items are related to the XX machine. This machine is responsible for an inbound flow of XX order lines per year.

A machine is divided into different modules, where each module is split into *production days*. Each production days consists of production orders. It is the task of the central warehouse to pick the items that correspond to the production order and deliver them on time at the manufacturing department. Figure 2.3 gives an example of how a machine is subdivided.

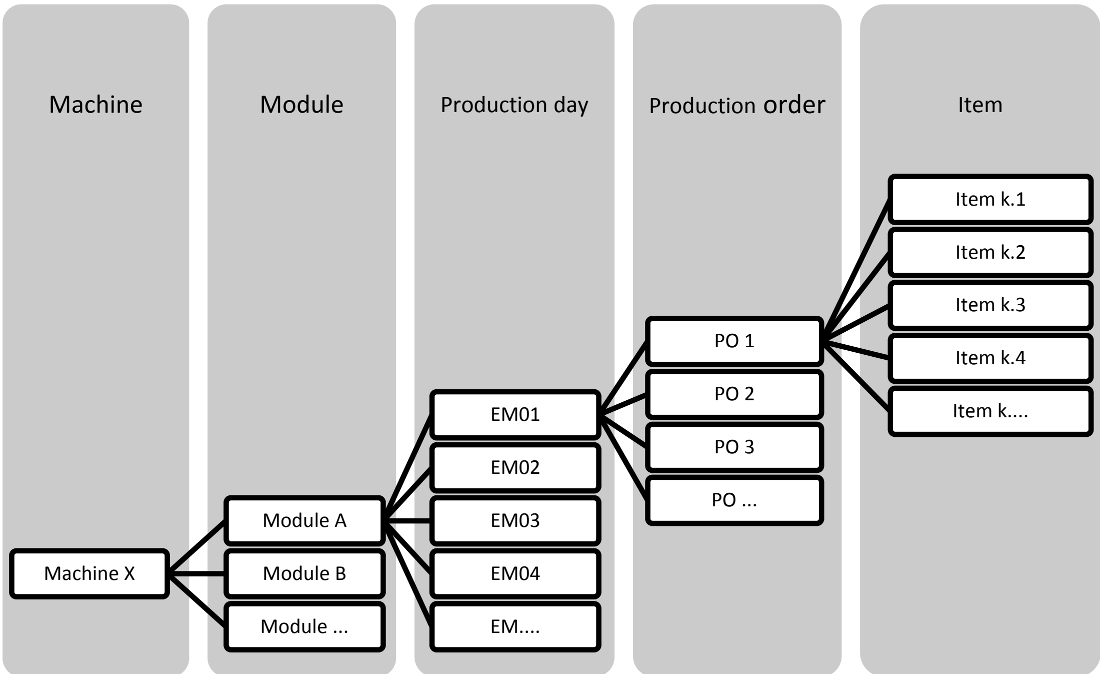

Figure 2.3: Overview of a subdivision of a machine at VMI Holland

2.2 Process description and data collection

In this section, we give a comprehensive description of the current warehouse processes of VMI Holland. We collect data on the current system structure and operating procedures of the VMI Holland warehouse. To gather this information, we study the processes, access the ERP system, and interview employees.

2.2.1 Material inbound flow

As described in Section 2.1, the inbound material flow of the central warehouse consists of two sources: items from suppliers and items from the anonymous warehouse. Therefore, the material that moves through the warehouse processes consists of two different flows:

i. The material flow that comes directly from suppliers: these items pass all warehouse activities from goods receipt till transportation to the production facility;
ii. The material flow that comes from the anonymous warehouse: these items are already received and accepted, and are directly put-away into storage locations at the central warehouse (arrow b in Figure 2.1).

The total number of items that has to be processed by the warehouse depends on the number of projects that are planned at the manufacturing department. When a production order is requested, the warehouse has to make sure they deliver the items on time. Next, we clarify per material flow, their operating procedure, and characteristics.

Materials from suppliers

When a new project is planned, the purchasing department receives a bill of material from the work preparation department that corresponds to a production order. It is the task of the purchasing department to buy project based items and make sure they arrive on time at the warehouse. The purchase department tries to agree a confirmed delivery date of 6 days in front of the start of a project. The anonymous warehouse makes sure that their items arrive 7 working days in front of the start of a project at the central warehouse.

On average XX items arrive per week by suppliers. These items arrive between 07:30 till 16:00 from Monday till Thursday, and till 14:15 on Fridays. VMI Holland has over XX different suppliers, delivering XX items at the time. There is a high variation in the delivery times of suppliers during a day.

Materials from the anonymous warehouse

The anonymous warehouse delivers the items to the central warehouse twice a day. 1/3rd of the items arrive at 9:00 and 2/3rd of the items 12:30 for that day. This material flow, with an average of XX articles per week, consists of items that move to the red box zone and euro pallet zone. These items enter the system in the buffer at the put-away stage. The anonymous warehouse starts picking their items 7 working days in front of the start of a project.

On average there lie around XX items in the warehouse (according to project storage location (16-06-2015). Figure 2.4 gives, per week, the inbound of materials of deliveries from suppliers and from the anonymous warehouse.

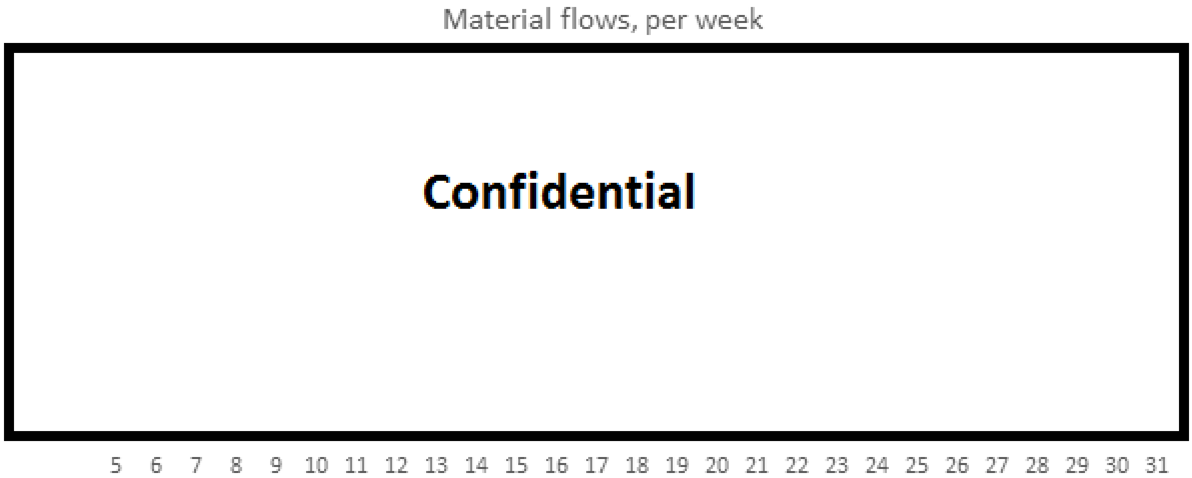

Figure 2.4: Inbound materials of anonymous and project based items, per week. (Source: inbound lines Infor week 5 - week 31 of 2015)

As we see in the figure, the total inbound of materials fluctuates from XX items till XX per week. The number of items that is expected to be received, for a certain day, determines the workforce of the inbound processes of the warehouse. The workforce planning of the inbound processes is based on a forecast of the expected receives for a certain day. Since the throughput of the working station is not known, an estimation based on experience is used to plan a workforce. Figure 2.4 shows per day, the percentage of deviation between the expected and actual arrived number of items.

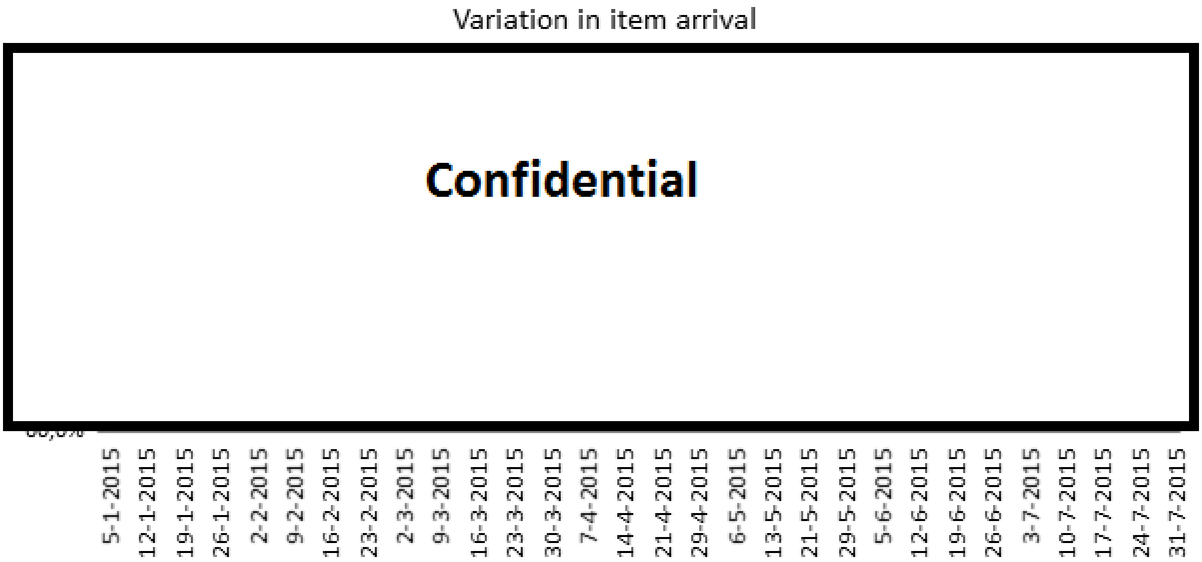

Figure 2.4: The percentage of variation of the expected arrival of items per day. (Source: ERP, 05-01-2015 till 31-07-2015)

As we see in the figure, there are only a few days whereat the expected arrivals closely correspond to the actual arrivals. This discrepancy makes it difficult to plan a workforce that corresponds to the actual inbound flow. When the warehouse expects XX items for a certain day, it is possible that there arrive XX items or XX items. Besides, it is also unknown at what time suppliers deliver their items. In the current situation, it is possible that on a certain day, the total inbound of materials is twice as much than expected. This variation in arrival leads to insufficient capacities at workstations.

2.2.2 Receiving stage

Suppliers deliver the items at the docking area at the front of the warehouse. Items then move to the receiving stage, where an employee compares the consignment with the order. When the amounts on the bill of lading correspond with the notification the items are entered into the ERP system. Next, the company's purchase-order and when necessary a set of in-house stickers, are printed and added to the item(s).

Workforce
All items that arrive need to be registered into the ERP the same day. Therefore, only for the receiving stage work in overtime is allowed. The receiving stage has a capacity of 3 working stations. The minimum occupation is 1 station.

Processing time
The processing time is not available in the public version of this report.

2.2.3 Accepting stage

After the receiving stage, the items move to the accepting stage, where the items get unpacked and assigned to a transport carrier. Based on size and weight, items move to different accepting stations based on the storage type. The different processing stages are:

- The accepting station for small and medium items: 93% of the items pass through this station;
- The accepting station for large and heavy items: 7% of the items pass through this station.

At each of these stages, an employee unpacks the items and checks if the article corresponds to the right quantity and description. If so, items are foreseen with in-house labels. Items are then, allocated to a transport carrier based on size and weight, according to Table 2.2. At the second station, the employees put-away the articles into the storage zones.

Table 2.2: Allocation of items to transport carries.

Transport carrier	Size	Weight	# of items on/in carrier
Red Box (RB)	smaller than 570mm	smaller than 18kg	8
Euro pallet (EP)	570-1200mm	>18kg	Max 7
Steel pallet (SP)	1200-1800mm	>18kg	Max 3
Self-supporting (ZD)	>1800mm	>18kg	1

Each transport carrier contains an identical bar-code. Items are registered to a transport-carrier by scanning this code with a portable scan device. Multiple items can be allocated to a single transport-carrier.

Workforce
The accepting station for items that fit a red box or a euro pallet can be subdivided into two stations that can process items fast (FAST-lane), and three stations that processes items normal (NORMAL-lane). The FAST-lane consists of 2 stations each having 3 employees: 1 employee actually 'accepts' the items by assigning it to a transport carrier, 2 employees unpack and prepare the items. There is a minimum occupation of 1 station. The NORMAL-lane consists of 3 stations, 1 employee per station, with the possibility that an employee unpacks the items.

The accepting station for items that are placed on a steel pallet or are self-carrying can be subdivided into a station for painted items (RAL-station) and a station for the rest (UGLY-station). The RAL-station and the UGLY-station has respectively a minimum occupation of 1 and 2 employees. In total, there is a maximum occupation of 8 employees. The employees at these stations bring the items to their storage locations.

Processing time
The processing time is not available in the public version of this report.

2.2.4 Put-away stage

The VMI Holland warehouse contains four storage zones, divided into two different buildings, where the large and heavy items are stored in one building and the small and light items in the other. Items are placed in storage locations, according to their size and weight. The large and heavy items that move into the steel pallet (SP) zone or self-carrying (ZD) zone are located in the same building as the receiving and accepting stage. The small and light items that move into the red box (RB) zone or euro pallet (EP) zone are moved from the acceptance stage, by a commuter around 4 times per hour, to the other building. Items that arrive from the anonymous warehouse move directly to the RB or EP storage zone. The characteristics of the warehouse storage zones are given in Table 2.3.

Table 2.3: Characteristics of the warehouse storage zones (source: ERP, June 2015)

Storage zone name	Type of storage location	# of locations	Fraction of total items stored	Avg. number of articles per location
Red Box	Boxes in racks	3,528	0.75	5.6
Euro pallet	Pallet racks	2,226	0.18	2.4
Steel pallet	Ground location	816	0.04	6.1
Self-carrying items	Ground location / hang location	370	0.03	7.9

At each storage zone, an employee puts the items into the designated storage location on advice of the ERP system. The system checks if there are items with the same project number already located in the storage zone. If so, the system responds a put-away advice of that same location. If not, the system responds the nearest empty storage location. Both the red box and euro pallet zone consists of racks that hold storage locations. The steel pallet zone consists of ground locations where the pallets can pile up to 3.5 meters, which correspond to 8 pallets. Self-carrying items can be stored in three different ways: (i) items are put on large steel pallets, (ii) items are put on cantilevers, or (iii) items are put on a large ground location. Those items have in common that they cannot be stored in one of the three previous described storage zones (RB, EP, and SP zone). The items are simply too heavy and/or too large. In this zone, articles do technically not lie on a storage device, but are the storage rack themselves.

Processing time of items in the red box zone (RB)
The processing time is not available in the public version of this report.

Processing time of items in the euro pallet zone (EP)
The processing time is not available in the public version of this report.

Processing time of items in the steel pallet zone and self-carrying (SP and ZD)
The processing time is not available in the public version of this report.

2.2.5 Picking stage

The picking system of the warehouse can be classified as a picker-to-stock type: a picker walks to storage locations to retrieve items. Entire storage locations with items are picked from the different storage zones, corresponding to a production order, and are merged together. Items are picked, four days in before the start of a project, according to a pick-list. Articles that are self-carrying are picked separately, because of their size and weight. These locations are picked two days in front of the start of a project. After scanning the bar code on the pick list, the scan device gives an advice based on the sequence of aisle number. At the storage zones, entire storage locations are picked. When the location is picked, the system marks the storage location as 'empty'. When the items are picked, they are not allocated to a location. The system marks these items as "*on stage"*.

Production-orders in the euro pallet (EP) and red box (RB) zone are picked by the same employee, because these zones are within the same building. Euro pallet locations are picked with an electric pallet truck and put on a steel pallet. Red boxes are picked with a cart and put on the same steel pallet. The articles from the steel pallet (SP) zone are picked separately, moved to the other building, and merged with the other items. Normally, the items from the SP zone are picked first, whereby the other items are merged. Items from the SP, EP, and RB zone are picked with a maximum of 6 employees at the time.

When a production order is incomplete, but necessary at the production facility, a material planner has to make a consideration, whether to delay the project or continue the process and wait for, or repurchase the missing item.

Processing time of the picking stage

The processing time is not available in the public version of this report.

2.2.6 Packaging and Transport stage

Before production-orders are packed and shipped to the production facility, they are checked for completeness and missing items at the scanning tables.

Scanning tables

To prevent delays in the production facility production orders have to be complete and correct. The scanning tables should identify and filter the errors that can occur during the (previous) warehouse processes. As soon as the item passes the scanning table, the item is booked out of a storage location. This item is now marked as "*transported*". There is no mutation in the system that registers the actual time of transportation. The output of the scanning-table is a list with missing items. When an order is incomplete, the missing items have to be found in the warehouse, lend from another order, or repurchased. In the last case, it can take several days until the item arrives at the warehouse, resulting in a delay of the project. In the other cases, additional proceedings; costing labour hours, have to be performed. In total there is a maximum of 5 scanning tables, each of them scanning around XX items per hour.

Packaging and transportation

When a production order is complete, an employee wraps the order and moves it to a temporary storage space in front of the shipping dock. According to an outbound planning, the production-orders are transported to the production facility one day before the start of the project. Orders with the same destination at the production facility are loaded together into the truck.

2.2.7 Outbound material flow

Each day at 00:00, a run is performed by the ERP system that checks the inventory of the warehouse. Based on this run, the material management department determines the (expected) completeness of production orders. If the order meets the desired items, the order is planned to be picked and moved to the manufacturing department. When a production order has to be picked, it can occur that items are according to the ERP system available but are not yet put away. Meanwhile, an employee picks a storage location, while some of the products are still at previous stages of the warehouse. Therefore, it is of great importance that items put into their locations on time.

The outbound of articles depends on start date of a production module (production order). Articles move one day ahead of this date to the production facility. When a production module is rescheduled later in time, the articles remain in the warehouse locations. The output of the warehouse is a stable process and easy to handle, according to the head of material management. Because the workload of the outbound process corresponds to the demand from the production facility the workforce is accurately predictable.

2.2.8 Warehouse resources

In this section, we describe the enterprise system VMI Holland uses and what resources are used within the warehouse.

Enterprise system

Since 2012, VMI Group makes use of the enterprise resource planning system: *Infor ERP-LN*. This system is the successor of the previous system Baan that was implemented in the year 2000. Infor LN is specialized for small and medium-sized manufacturing companies and can handle complex and global operations. The system is able to support logistic processes within the organisation, such as make-to-stock, make-to-order, assemble-to-order, and engineer-to-order. Within the warehouse of VMI Holland, Infor LN keeps track and the allocation of items to storage locations. Scan-devices and custom made data tables are used to communicate with the ERP whenever items are stored or picked in locations. The mutations into the ERP system of each warehouse activity are given in Appendix B.

Working hours

The working day starts at 07:30AM and ends at 16:15PM. There are two breaks scheduled, a quarter of an hour at 9:30AM and a lunchbreak of half an hour at 12:30PM. During breaks, no item is processed.

Put and pick equipment

Since the warehouse needs to be portable, there are no automatic pick or storage processes. The transportation of larger components between storage zones happens with a forklift truck. The transportation within these zones happens for steel- and euro-pallets with an electric pallet truck. Carts are used to put and pick red boxes. The warehouse makes no use of a conveyor belt or other automatic storage equipment.

Personnel

Due to the high variation in arrival of items, it is hard to predict how many employees each workstation needs. The scheduling of workforce is based on experience of the foremen. Besides the workforce that is responsible for the processing of the normal material flow, there is a supportive workforce responsible for missing items, back orders, item rejects, trouble-shooter, and sub-contracting.

2.3 Current performance measurement

Currently, the head of material management keeps track of four performance indicators of the warehouse:

- *Completeness of production order:* measures per week, the number of production orders that is complete divided by the total number of production orders that week;
- *Completeness of item outbound:* measures per week, the total number of items that is present at the moment of transportation, divided by the requested number of items;
- *Storage occupation:* measures for each week the occupation of the euro pallet and red box storages zones;
- *Workforce efficiency:* measures each week the workload divides the workload by the number of working hours, where the workload is determined by an estimation of the number of items that move through the warehouse.

As we have seen in the Section 2.2.1, the variation in item arrivals of suppliers ask for performance indicators that make sure items are placed on time into their storage locations, workstations become efficient and effective. With the current indicators, the head of material management and the foremen are limited in adjusting capacities in order to improve efficiency. In Chapter 4, we determine with the help of a stakeholder's analysis and performance indicators from the literature study, what indicators fit VMI Holland's needs.

2.4 Conclusion

In this chapter, we described the current activities and material flows of the VMI Holland warehouse. We have identified two material flows the warehouse has to cope with. The first material flow comes directly from suppliers and arrives at the docking station of the warehouse, XX items on average per week. Discrepancy in the expected arrivals and the actual arrivals of items makes it hard to make an adequate workforce planning and lead to insufficient capacities at workstations, causing inefficient processes and a poor performance of the inbound system. Besides, the arrival of items during the day variates and is unpredictable. 75% of the items are small and belong to the red box zone, 18% of the items end up in the euro pallet zone, and the rest of the materials end up on a steel pallet (4%) or is self-carrying (3%).

The second material flow comes from the anonymous warehouse and delivers items for the red boxes and euro pallets storage zones. This flow consists on average of XX items per week and has a relatively constant arrival time. 90% of these items arrive in red boxes and 10% in euro pallets.

The outbound material flow depends on the planned production orders at the manufacturing. The workload of the outbound process is easy to predict allowing the foreman to make a workforce planning that matches the demand of capacity of the workstations. The outbound planning is based on a run from the ERP system that is performed at night and determines the completeness of orders. Therefore, it is of great importance that items are put into their storage locations on time or items have to be picked, while they are not placed into their storage locations yet.

We have seen that VMI Holland has limited insight into the performance of their processes. The company uses four performance indicators to measure the warehouse performance: (i) completeness of production orders, (ii) completeness of item outbound, (iii) storage occupation, and (iv) workforce efficiency. In the next chapter, we create a set of indicators that help VMI Holland to measure and control its processes and to measure the output of the simulation model.

3. Theoretical framework

In this chapter, we seek for performance indicators for the VMI Holland warehouse at the strategic, tactical, and operational level. We make use of reliable literature sources such as: Scopus, Web of Science, Science Direct, and Google Scholar. In Section 3.1, we identify the main function of a warehouse and the characteristics of its activities. In Section 3.2, we perform a literature study to find performance indicators and metrics that are commonly used for warehousing. Finally, in Section 3.3, we give a conclusion.

3.1 The warehouse function

In this section, we describe the characteristics of a warehouse. In Section 3.1.1, we describe the main function of a warehouse as part of a supply chain. In Section 3.1.2, we describe the activities that take place within a warehouse. In Section 3.1.3, we explain what resources are needed to perform these warehouse activities. Finally, in Section 3.1.4, we describe the function of a warehouse management system.

3.1.1 The definition of a warehouse

Warehouses are an important component of any supply chain (Gu, Goetschalckx, & McGinnis, 2006). The primary aim is to facilitate the movement of goods from the suppliers to customers in a timely and cost-effective manner. Warehouses perform as a valuable function that supports the movement of materials. A warehouse has three important functions: (i) to bridge the interval of time between the moment that items are received and the moment that they are needed, (ii) to change the composition of the goods, and (iii) to guide items to their destinations. From a business and management point of view, the warehouse equipment takes up space and ties up fixed assets (Kappauf, Lauterbach, & Koch, 2012).

The design of a warehouse often demands a high investment and comes with a lot of trade-offs and challenges. All decisions have a direct impact on the effectiveness and efficiency. At the strategic stage of warehouse design, decision regards to organisations, strongly affect the selection of hardware means that will be installed, such as the layout of the warehouse, type of equipment, and the dimension of capacities on the long term. The layout of a warehouse varies on the demand forecast and a desired flexibility that allows growth. Some organisations decide to outsource the entire warehouse when the throughput volume is low and the demand variability fluctuates. At the tactical stage, decisions are made regarding the dimensions of warehouse processes and workforce. Important decisions involve the dimensioning of the picking zones, picking policies, and storage methods. At the operational stage, decisions include task assignment to people and equipment, allocation of incoming goods to storage locations, assignment of picking task to order-pickers, and batch formation or order sequencing.

Gu et all (2007) made a scheme to classify warehouse design and operation planning problems. The warehouse design problems are given in Table 3.1. The operation planning is described in the next section.

Table 3.1: Description of warehouse design problems (Gu, Goetschalckx, & McGinnis, 2006)

Warehouse design problems	Decisions
Overall structure	• Material flow • Department identification • Relative location of departments
Sizing and dimensioning	• Size of the warehouse • Size and dimension of departments
Department layout	• Pallet block-stacking pattern • Aisle orientation • Number, length, and width of aisles • Door locations
Equipment selection	• Level of automation • Storage equipment selection • Material handling equipment selection
Operation strategy	• Storage strategy selection • Order picking method selection

3.1.2 Warehouse activities

Warehouses can have different activities according to product specification, customer requirements, and service levels offered. The complexity of the warehouse activities depends on: (i) the number of variety of items to be handled, (ii) the amount of daily workload the be done, and (iii) the number, nature and variety of processes necessary to fulfil the needs and demands of the customers and suppliers (De Koster & Warffemius, 2005). Although the requirements of different warehouse centres are diverse, each system includes standardized processes: receiving, put-way, order picking, and shipping (Hompel & Schmidt, 2007). Figure 3.1 gives a visualisation of the main warehouse processes.

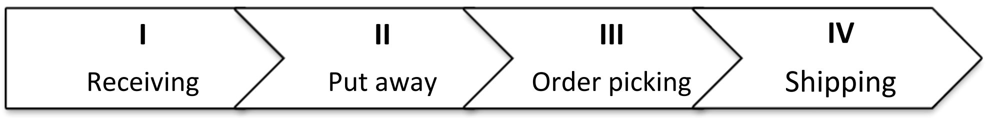

Figure 3.1: Warehouse functions according to Hompel & Schmidt (2007)

Out of these activities, receiving and put-away belong to the inbound logistics and are concerned with the incoming flow of materials into the warehouse. Order picking and shipping belong to the outbound logistics and are concerned with the flow of materials that move out of the warehouse. In the next section, we give for each of the functions a description of the processes and the important decisions that are involved.

I: Receiving stage

The receiving stage is the first important step in the material flow of a warehouse. The main task of this stage is to unload, check, and inspect the arriving items. When goods are accepted, they are recorded in the enterprise system such that the inventory levels are updated and the warehouse management system can track the items. Items are provided with in-house labels for internal identification. In the next step, the consignment is submitted to a physical check. Extensiveness of the inspection is based on company’s rules. These inspections may be a simple test or a complete full-scale control. Faulty products are marked and removed from inventory. Finally, the weight and dimensions of an article is determined to optimize the volume utilization of the warehouse. The goods have to be re-palletize into the company’s specific containers.

II: Put-away stage

The main task of the put-away stage is to move the goods to their storage locations. The first step in the storage process is the determination of the storage bin. The type of storage bin is determined according to a variety of criteria, which results from: the physical requirements of the goods to be stored, the operational and technical warehouse operation, and security and legal regulations (Hompel & Schmidt, 2007). Based on these criteria, a variety of strategies can be used to optimize the operating process of a warehouse system. Three fundamental decisions shape the storage function (Gu, Goetschalckx, & McGinnis, 2006):

1. How much inventory should be kept in the warehouse;
2. How frequently and at what time should the inventory be replenished;
3. Where an item should be stored in the warehouse and distributed and moved among the different storage areas.

Important criteria that influence these decisions are the storage efficiency, which corresponds to the holding capacity, and the access efficiency, which corresponds to the resources needed by the storage and order picking processes (Gu, Goetschalckx, & McGinnis, 2006).

III: Retrieving (picking) stage

Order picking is the process of retrieving items from storage to meet a specific customer order. This process is known to be the most labour-intensive and costly function among all warehouse functions (Manzini, 2012). The retrieval function has a critical impact on downstream customer service. Customers expect quick and accurate processes of their orders. Order picking systems can be classified into two types (Manzini, 2012):

- Picker-to-stock: a picker walks or rides to storage locations to retrieve items;
- Stock-to-picker: the storage location of the requested item is brought to the picker.

Three areas of a traditional order-picking system can be identified (Hompel & Schmidt, 2007):

- Material flow system: how are pickers and articles brought together most efficiently;
- Organizational forms: the arrangement of the storage areas and the performance of picking processes;
- Information processing: the collection, preparation and processing of all information which are necessary for the order-picking.

After goods have been retrieved, the inventory is updated by reducing the stock by the retrieved quantity.

IV: Shipping stage

At the shipping stage orders are inspected, packed, and loaded into trucks, trains or other carriers. Basic operation decisions involve the allocation and dispatching of material handling resources, such as labour and material handling equipment.

Warehouse operation problems

Gu et al (2007) made a scheme to classify warehouse design and operation planning problems. The warehouse operation problems are given in Table 3.2. This framework describes the decisions that appear in warehouse operations. To perform optimally, these problems have to be formulated and implemented in a proper way.

Table 3.2: Description of warehouse design problems (Gu, Goetschalckx, & McGinnis, 2006)

Warehouse operation problems		Decisions
Receiving and shipping		• Truck-dock assignment • Order-truck assignment • Truck dispatch schedule
Storage	SKU-department assignment	• Assignment of items to different warehouse departments • Space allocation
	Zoning	• Assignment of SKUs to zones • Assignment of pickers to zones
	Storage location assignment	• Storage location assignment • Specification of storage classes
Order picking	Batching	• Batch size • Order-batch assignment
	Routing and sequencing	• Routing and sequencing of order picking tours • Dwell point selection (for AS/RS)
	Sorting	• Order-lane assignment

3.1.3 Warehouse resources

Resources refer to all means, equipment and personnel needed to operate a warehouse (Rouwenhorst, et al., 2000). To perform the processes within the warehouse in effective and efficient way, resources have to be allocated in an optimal cost and capacity way. According to Rouwenhorst (2000), we can distinguish a number of common resources in warehouses:

- The *storage unit*, in which products may be stored;
- The *storage system*, the way the items are stored;
- The *pick equipment*, that stores and retrieves the products in storage units;
- *Order-pick auxiliaries*, equipment that supports the order-picker e.g. bar code scanners;
- *A computer system*, to enable computer control of the processes by a warehouse management system;
- The *material handling equipment,* for preparation of the retrieved items for the expedition e.g. sorter system, palletizers, and truck loaders;
- The *personnel that* performs all the warehouse processes.

All these resources make sure that the warehouse activities can be executed.

3.1.4 Warehouse management system (WMS)

Software for warehouse logistics and inventory appeared for the first time in the 1970s. These warehouse systems were pure stock management systems with the goal to maintain quantities and locations within a warehouse and their relation to one another. Modern warehouse management systems are key part of the supply chain and primarily aim to control the movement and storage of materials within a warehouse. These systems are capable of continual optimization control and supervision of material flow, equipment and staff, from goods receipt through all warehouse and processing steps (Kappauf, Lauterbach, & Koch, 2012). The system tracks inventory from the point of receipt to the point of shipment. WMS required a host system to interface to the *enterprise resource planner* and other data such as purchase order data, sales data, and item master data. Most companies use a WMS for inventory accuracy, improvement of productivity, visibility, and customer compliance (Severance, 2011).

3.2 Performance indicators for warehouse processes

In this section, we compose a list of performance indicators that enables performance measurement at the warehouse environment. In Section 3.2.1, we describe the meaning of performance management in organisations. In Section 3.2.2, we describe how performance indicators contribute to performance measurement and to what requirements indicators should satisfy. Finally, in Section 3.2.3, we seek for indicators and metrics that are commonly used in the literature for logistic and warehouse performance measurement. To find relevant literature, we make use of several literature databases, such as *Scopus, Web of Science, and Google Scholar.*

3.2.1 Performance management

Performance is everything that contributes to the company to reach strategic objectives (Lorino, 2003). The aim of performance management is to ensure that running processes are subject to constant improvement through continuous measurement and analysis (Scheer, 2006). It provides a structured approach for focusing on a program's strategic plan, goals, and performance. Performance measurement focuses on what is to be accomplished and compels organizations to concentrate time, resource, and energy on achievement objectives.

Performance can be evaluated in an economic way with the use of a financial report, and a physical evaluation via performance indicators. As a process, performance measurement is not simply concerned with collecting data associated with a predefined goal or standard, but is a better thought of as an overall management system involving prevention and detection of a process. In this way rearrangement of resources is possible so that capacity meet its demand. With this knowledge, a company is able to adapt to a more appropriate situation.

3.2.2 Performance indicators

Fortuin (1988) defined a performance indicator as: "*a variable indicating the effectiveness and/or the efficiency of a part or whole of the process system against a given norm/target or plan"*. With performance indicators we can compare actual results with a pre-set target, and measure the extent of any deviation.

According to Carter (1991), there are some characteristics that make a good performance indicator (PI). First, a PI should be relevant to the needs and objectives of the organisation: they should measure aspects of performance that are central to efficient and effective delivery of the quality outcomes. The indicator should not be sensitive to manipulation by the users. Secondly, PI's should be reliable, based on relevant data from accurate information systems. As a practical organisational tool, it is essential that PI's are both comprehensive and usable. The number of indicators should be compact and not extensive.
Doran (1981) has defined that *"There's a S.M.A.R.T. way to write management's goals and objectives"*. He defined criteria that guide the setting of objectives in performance measurement. Therefore, performance indicators should be:

- Specific: the indicator should describe a clear target for measurement;
- Measurable: the should be a method or procedure to measure the indicator;
- Attainable: within the person's ability and resources to achieve the goal;
- Realistic: the norm of the indicator should be achievable and realistic;
- Time-related: the indicators should be measured in a timeframe.

We use the criteria defined by Carter and Daron in Section 4.2 to create list of indicators for the processes of the VMI Holland warehouse.

To decide whether a performance deviates from a desired situation, the indicator must be related to a norm or standard. A company should define a set of actions or make adjustments to ensure standard gets realized. A norm can be set, based on three types of values: historical, base, or standard (Caplice & Sheffi, 1994). With the use historical values, trends over time can be analysed, but is less robust, since it is not comparable across firms. Comparing against base values e.g. total logistic costs or total distribution cost increases the robustness, since a better comparison across firms can be accomplished, but is less controllable by a manager (Caplice & Sheffi, 1994). Comparing against standard is more a control tool, since it tracks whether a process or project sticks to its plan.

3.2.3 Performance indicators and metrics for warehouse processes

In Section 3.1, we described the main function of a warehouse and its processes. In this section, we seek the literature for performance indicators for warehouse processes. Assessing warehouse performance lacks in the research literature. Most literature focuses on a single warehouse optimisation or methodology, such as: storage optimisation, warehouse design, throughput, and routing and order picking problems. However, Staudt (2015) has extracted this information from papers and transformed it in summarised results, focussing on operational warehouse performance evaluation. The article: "*Warehouse performance measurement: a literature* review" makes a distinction between direct and indirect indicators. Direct indicators, also known in the literature as hard metrics, which treats quantitative measures such as order cycle time, fill rates, and costs. Indirect indicators, also known as soft metrics, deals with qualitative measures like customer satisfaction and loyalty. The direct indicators are relatively easy to measure using mathematic tools while soft indicators require more advanced tools (Staudt, Alpan, Di Mascolo, & Rodriguez, 2015).

Direct indicators are divided into four performance evaluation dimensions that are commonly used in industries: *time, quality, cost,* and *productivity.* Where direct indicators can only be assigned to one dimension, indirect indicators can be measured in association with several dimensions. Subsequently, the direct indicators can be further classified according to warehouse activities and processes. A list of the direct and indirect performance indicators adapted from Staudt is given in Appendix C.

To measure the current state of a process, we expand the literature study by searching for performance metrics for supply chain processes. The different stages within the warehouse can be seen as processes in the supply chain. Since processes have an input, process and output structure, we can measure three additional dimensions of performance metrics: utilization, productivity, and effectiveness (Caplice & Sheffi, 1994)**.**

Utilization metrics
Utilization metrics track the use of input resources in a process. According to Caplice (1994), non-financial resources should be measured with the use of ratio's, which compares the assets actual output with the amount available. Inventory measures of process utilization can be divided into static metrics and flow metrics. Static metrics measures the level of inventory at a specific point in time. Flow metrics measure the speed of inventory when it flows through the system.

Productivity metrics
The productivity metric measures the transformational efficiency of a process, comparing the actual outcome with the input consumed. Productivity can be measured focussing on a single process or take an entire systems into account.

Effectiveness metrics

Effectiveness is a measure of the quality of process output. Andersson et al. (1989) have identified two types of effectiveness measures: the *ability* to deliver according to a certain demand, and the *reliability* to deliver according to a certain promise.

Appendix C gives an example of utilization, productivity, and effectiveness metrics adapted from Andersson et al. (1989).

3.3 Conclusion

In this chapter, we gave the theoretical framework of the research. First, we described the context of the research. We identified three important functions of warehouses: (i) to bridge the interval of time between the moment that items are received and the moment that they are needed, (ii) to change the composition of the goods, and (iii) to guide items to their destinations. We identified four common warehouse activities: receiving, put-away, picking, and transportation. At each of these stages, decisions have to be made that influence the performance of the warehouse.

Second, we clarified the importance of performance measurement and gave characteristics of proper performance indicators. The indicators we select for VMI Holland should be: specific, measurable, attainable, realistic, and time related. We found indicators and metrics in the literature that VMI Holland can use to measure the performance of its warehouse processes. The result is a list of indicators from Staud et al. (2015) that includes performance indicators for the warehouse environment, and indicators from Andersson et al. (1989) that includes performance metrics for processes in the supply chain environment. In Chapter 4, we make a selection of the performance indicators and metrics for the VMI Holland warehouse.

4. Performance measurement for VMI Holland

In this section, we select performance indicators that VMI Holland can use to measure and control its warehouse processes at the strategic, tactical, and operational level. In Section 4.1, we identify the main stakeholders that involve or affect the activities of the warehouse. In Section 4.2, we select the indicators that fit the needs of VMI Holland with the main stakeholders. In Section 4.3, we customize the indicators to VMI Holland and give per indicator, the definition, the measurement method, the formula, the norm, the frequency of evaluation, how to measure, and how to react. In Section 4.4, we give the shortcomings of the ERP system. Finally, in Section 4.5, we give the conclusion.

4.1 Stakeholders analysis

There are many different definitions for stakeholders. Freeman has defined a stakeholder as: "A *stakeholder in an organization is any group or individual who can affect or is affected by the achievement of the organization's objectives*" (Freeman, 1984). For this thesis, we identify the groups or individuals who can affect or are affected by the warehouse processes and/or the material flow. We list the stakeholders of the warehouse processes, in order of importance and influence:

- *The head of material management (manager of the warehouse)* that represents the management team of VMI Group, wants to perform operations in an efficient and effective way at lowest costs. The management team strives for zero errors in the material flow. They want to avoid work in overtime and perform the processes at high efficiency at lowest costs. The manager can affect processes by influencing the available capacity at the strategic and tactical level;
- *The foremen of the inbound and outbound processes* that control the processes at the operational level. The foremen are responsible for the processing of the items that flow through the warehouse. The foremen have interest in the utilization and throughput of the processes, in order to adjust the capacity;
- *The suppliers* affect the inbound process of the warehouse by determining the point in time and the way they supply goods. The variability in arrival times determines the workload of the inbound warehouse processes;
- *The warehouse employees* are affected by the processes and activities that have to be performed. They affect the output of the warehouse due to the activities they perform, that indirectly affects the capacity performance of the warehouse;
- *The mechanics (production)* are affected by the output of the warehouse. They want to receive a complete and error free set of articles from the warehouse department. They also desire fast delivery of (back) ordered articles. A delay in manufacturing can cause a delay in the entire manufacturing line;
- *The anonymous warehouse department* affects the warehouse with items that flow through the warehouse. They have to deliver the goods to the central warehouse on time and the correct number of items;
- *The logistic service team* is affected by the errors that occur due to incomplete or wrong output of the warehouse processes. They operate as a bridge between manufacturing and the warehouse. High priority deliveries are arranged by the logistic service team;
- *The purchase department* affects the inbound of the material flow and is partly responsible for the completeness of production orders. The department affects the amount and daytime items are delivered. Articles arrive too late: production orders cannot be picked and a delay occurs at the manufacturing department. Items arrive too early: storage locations are occupied for a longer period of time;
- *The work preparation department* affects the outbound of the warehouse by the size of (sub)modules that have to be picked and the day they are needed for manufacturing;
- *Shareholders* are affected by the performance of the entire organisation. They want a well-organized healthy organisation.

Head of material management is the most important stakeholder and the main user of the performance measurement. His interest lies with indicators and metrics of measurements that affect the resource capacity planning at the tactical and strategic level, such as the capacity dimensioning and the allocation of that capacity. Suppliers influences the workload of the inbound process and completeness of deliveries, affecting the performance of the warehouse. To deal with the variability in the workload of processes, the foremen are interested in an up-to-date performance indication of the receiving, accepting, put-away, pick, and transportation processes. They need insight into the throughput, queue lengths/times, and the productivity of processes.

4.2 Selection of performance indicators and metrics

The selection method of the performance indicators and metrics is visualized in Figure 4.1. We combined the indicators and metrics from the literature study with the stakeholder's analysis. The performance measures must comply with the scope of the research and to the S.M.A.R.T. criteria.

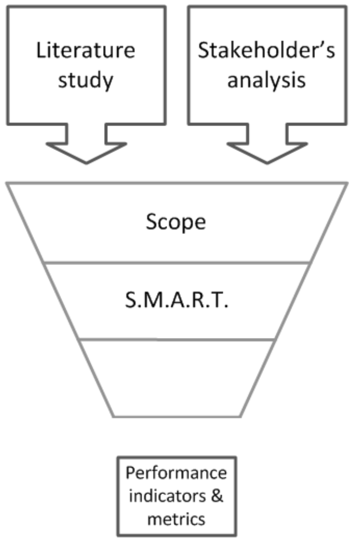

Figure 4.1: Selection method for performance measurement

The selection of the performance indicators is visualized into "The performance wareHouse of VMI Holland", shown in Figure 4.2. The house is a combination of indicators that should be updated continuously and help control the current warehouse situation. This house consists of different layers that represent levels of decision making. The roof of the house consists of the general warehouse performance, and supports the head of material management to make strategic and tactical capacity resource decisions. These indicators give insight into the overall performance of the warehouse and include: the workforce flexibility, the total utilization, average queue times/length, and the total throughput.

Underneath the roof contains indicators that are subdivided into the warehouse activities. These indicators give insight into the performance of the activities at the tactical and operational level and include: dock to stock time of items, order lead time of items, processing times, productivity of workstations, storage accuracy, shipping accuracy, on time delivery, and the queue length and time for each process. The indicators can be used by both head of material management and the foremen.

The bottom of the house consists of indicators that give insight into the performance of the storages zones and allows decision making at the operational level. These indicators, provides a foreman with accurate information on the material flow during a working day. These indicators include per storage zone the: throughput, queue length and time, and utilization.

In order to measure these indicators, we give in Section 4.3 for each indicator: a description, the measurement method, the formula, the norm, how to measure, how often, and how to act.

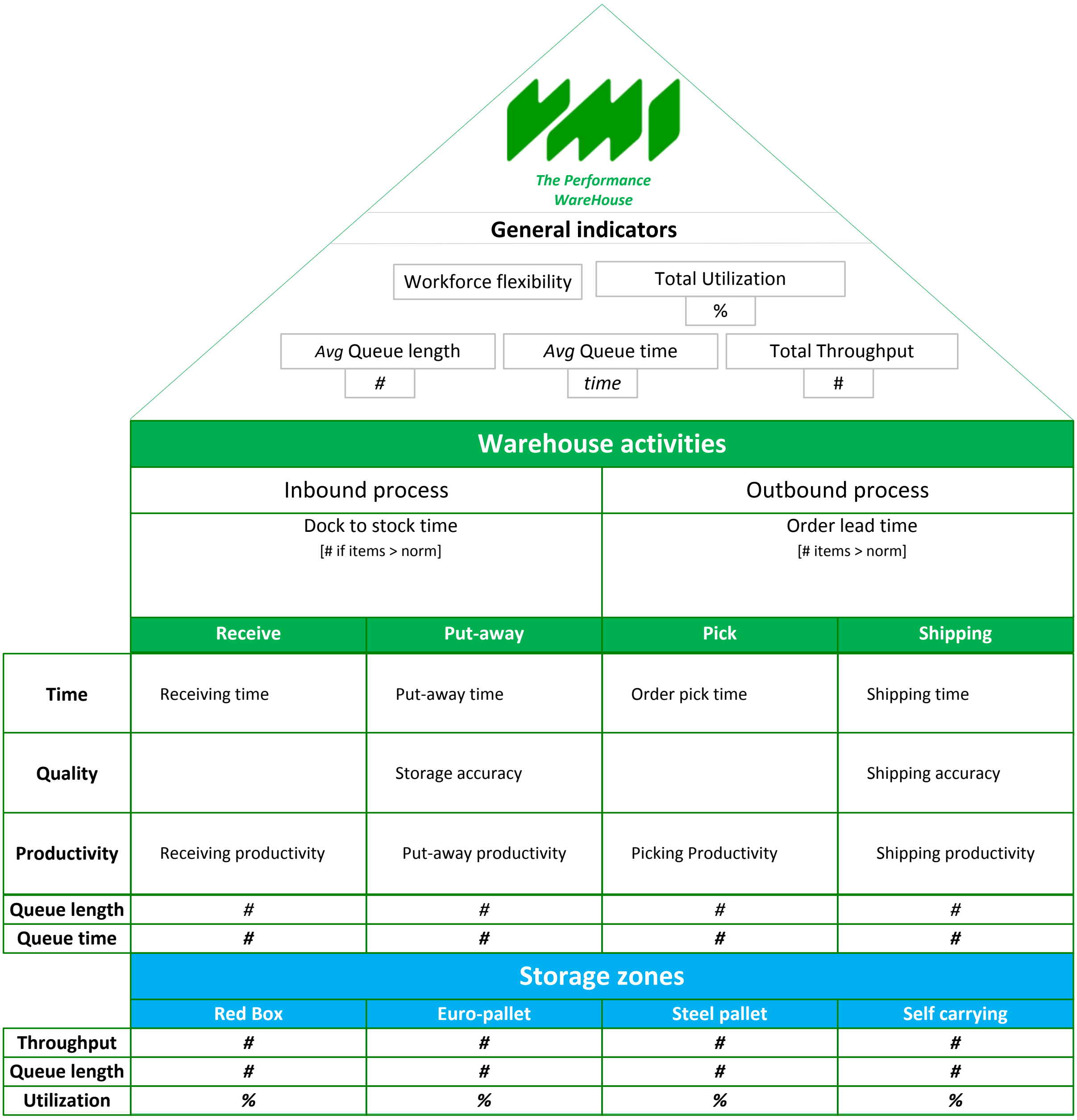

Figure 4.2: The performance wareHouse of VMI Holland. A representation of the performance indicators for the VMI Holland warehouse.

4.3 Definition performance indicators and metrics for VMI Holland

In this section, we give the definition for each performance indicators that allows VMI Holland to measure its performance and allows the company to control the performance. Therefore, we give for each indicator the description, the measurement method, the formula, the norm, how to measure, the frequency of evaluation, and how to act. We define the indicators according to the level of decision making, from the top to the bottom of Figure 4.2. First, in Section 4.3.1, we describe the general warehouse indicators. Secondly, in Section 4.3.2, we describe the indicators for the warehouse activities. Since the indicators of the storage zones are part of the indicators of the general indicators, we describe them in Section 4.3.1.

For the description of the indicators, we make use of the theory founded in the literature study and adapt it to the situation of VMI Holland. Normally, each performance indicator has a norm to identify any discrepancy between the measured situation and the desired situation. However, some indicators are selected to give insight in the progress of a process and help make decisions. The indicators that do have a norm are determined by interviewing the stakeholders (Section 4.1) that are involved.

4.3.1 General warehouse performance indicators

In this section, we define the general warehouse performance indicators that involve decision making at the strategic and tactical level.

I. Performance indicator: Warehouse storage utilization

Description:

The warehouse utilization indicates how well the storage capacity is being utilized, which is a direct result of the management of resources. A high utilization can be an indication of an inefficient storage strategy or agreements with suppliers. The utilization can be split into the four storage zones that consist in the warehouse. Each of these zones has a different norm that depends on the simplicity to adjust the capacity. We make a distinction of users of the indicator:

- The *foremen* want to know when to increase the current storage capacity at the (online) operational level. Inventory locations are blocked to increase storage efficiency. When a boundary of capacity limitation is met, these locations have to be unblocked to increase the current capacity. The locations that are open for storage, is defined as 'practical storage locations';
- The *head of material management* wants to know when the theoretical maximum utilization of the warehouse is met. He/she can make decisions at the tactical or even strategic level to increase the storage capacity.

Measurement method*:*

The number of storage locations occupied compared with the practical (foremen) or theoretical (management) capacity.

Formula:

$$Total\ utilization = \frac{\sum Utilization\ storage\ zone\ (z)}{total\ number\ of\ storage\ zones}$$

(z= 1: RB zone, 2: EP zone, 3: SP zone, 4: ZD zone)

The utilization per storage zone is determined for the head of material management:

$$Utilization\ storage\ zone\ (z) = \frac{total\ storage\ locations\ occupied\ (z)}{total\ theoretical\ storage\ locations\ (z)}$$

The utilization per storage zone is determined for the foremen:

$$Utilization\ storage\ zone\ (z) = \frac{total\ storage\ locations\ occupied\ (z)}{total\ practical\ storage\ locations\ (z)}$$

Norm: (both theoretical and practical storage locations)

- SP-zone: max 80%
- ZD-zone: max 80%
- RB-zone: max 75%
- EP-zone: max 80%

How to measure:

This indicator can be measured with data from the ERP system. The company has insight into what items are placed into what storage locations. It is of great importance that the company updates the theoretical and practical number of locations according to the actual situation to get the real value.

Frequency of evaluation:
Once an hour.

How to act:
When there is still a gap between the practical and theoretical locations, the foreman can easily increase the storage capacity by 'opening' storage locations that are now on 'reserve'. When the theoretical storage limit is reached, there is a need for new physical storage locations. The head of material management needs to react when the theoretical locations meets its maximum.

II. Performance indicator: Queue time

Description:
The queue time indicates the time items have to wait in front of a station till they get processed. A queue has a direct influence on the lead time of an item and indicates a possible bottleneck of the process. The capacity of the process can be adjusted to reduce the waiting time. No queue can be an indication of overcapacity. We divide the indicator into sub indicators, each measuring the queuing time of a warehouse process. The norm is set by the head of material management and the foremen of the processes.

Measurement method:
The (average) amount of time an items spends in queue in front of a workstation before it is processed.

Formula:

$$Total\ average\ queue\ time\ (p) = \frac{1}{n}\sum_{i=1}^{n} waiting\ time\ (i, p)$$

(p= process: 1: accept, 2: put-away, 3: picking, 4: shipping, i: item 1…n)

For:

$$Queue\ time\ process\ (put\ away) = \sum queue\ time\ storage\ zone\ (z)$$

(z= storage zone: 1: red box, 2: euro-pallet, 3: steel pallet, 4: self-carrying)

Norm:
- Accept process: max 4 hours;
- Put-away process: max 4 hours;
- Scanning process: max 4 hours.

How to measure:
To determine the queue time of the accept process, we can use the 'Status5' list that gives the number of items and duration of items that are registered in the system but waits to get accepted. Unfortunately there is no insight whether the items lie in queue in front of the accepting stage of the RB/EP or SP/ZD workstation. We can determine the time in queue for the put-away process by using output from the ERP according to transport carriers items are in.

Frequency of evaluation:
Once every 15 minutes.

How to react:
When a process exceeds its norm, the foreman has to increase the capacity of the process in order to decrease the queue time. A short or no queue time may indicate overcapacity at a process and can trigger the foremen to shift employees. A high queue time in combination with a low queue length may indicate an unproductive situation.

III. Performance indicator: Queue length

Description:
The queue length gives an indication of how many items have to be processed at an activity. In contrast to the indicator *queueing time,* this indicator measures the number of items in a queue instead of waiting time. A queue in front of a process indicates a disruption and can cause a delay in the system. With this information a foreman is capable to adjust capacities. Per process we set a different norm, whereby actions have to be performed to reduce the queue. Norms are set based on a maximum backlog VMI Holland thinks it can handle within 2 hours.

Measurement method:
The (total) number of items in a queue in front of an activity.

Formula:

$$Total\ queueing\ of\ process\ (t) = \sum queues\ process\ (p)$$

(p= process: 1: accept, 2: put-away, 3: picking, 4: shipping, t=time)

For:

$$Queue\ process\ (put\ away) = \sum queue\ storage\ zone\ (z)$$

(z= storage zone: 1: red box, 2: euro-pallet, 3: steel pallet, 4: self-carrying)

Norm:

- Accepting process: max 200 items;
- Put away process:
  - SP-zone and ZD: 100 items;
  - RB-zone: 200 items;
  - EP-zone: 150 items
- Shipping (scanning) process: 100 items.

How to measure:
The determination of the queue length of the process is equal to the queue time indicator. The indicator has to be measured constantly to foresee delays at processes.

Frequency of evaluation:
Once every 15 minutes.

How to react:
Structurally high queue lengths, indicates a mismatch of capacities at workstations and might be a trigger for the head of material management to invest in new resources or work policies. When there is a skew in the number of items in queue at different process, the foremen can move employees from one process to another in order to reduce the queue length. The foremen must foresee these inequalities of workload distribution to prevent accumulations and a skew in workload distribution.

IV. Performance indicator: Workforce flexibility

Description:
To shift personnel across the warehouse processes, employees must have the competences to work at different working stations. The workforce flexibility measures the degree, of at how many different stations an employee can work. In an environment with high variation in the demand of capacity, it is important to remain flexible. In times of shifting capacity demands or sickness, flexibility makes it easy to fill these needs. A competence matrix of the employees is needed to measure this indicator.

Measurement method:
The degree to which employees have the competences to work at different stations.

Formula:

$$Workforce\ flexbility = \frac{1}{N}\sum_{i=1}^{N}(\frac{\#\ of\ competent\ working\ stations\ (i)}{total\ number\ of\ working\ stations})$$

(N= total number of employees, i= employee 1..N)

$$Degree\ of\ workforce\ flexibility = \frac{\sum employees\ capable}{total\ employees}$$

Norm:
An employee must be able to work on at least three different working stations.

How to measure:
For each employee at the VMI Holland warehouse, its competences have to be recorded in a document file or competence matrix. When making the workforce planning for a certain period, the foreman has to keep the competences of the employees into account. There should be a wide diversity of competences during a working day.

Frequency of evaluation:
Once a month, the competences of the employees must be updated in a document file. New employees have to be added to this file.

How to react:
When there is a lag of competences, the employees must develop competences or the company should hire employees with the desired competences.

V. Performance indicator: Throughput

Description:
The throughput indicator measures the amount of items that are processed by a process during a certain time interval (hourly, daily, or weekly). With knowledge of the throughput per time unit, the arrival rates of the preceding process, and the queue length, the manager is capable of adjusting the capacity of the process that matches the workload. A low throughput in contrast with the amount of items in queue could be a trigger to increase capacity in order to increase the throughput.

Measurement method:
The number of items *i* that are processed by working station *p* during a certain time interval *t*.

Formula:

$$Throughput\ = number\ of\ items\ processed\ (t,p)$$

(p=receiving, accept, put-away, pick, shipping}, z={red-box zone, euro pallet zone, steel pallet zone, selfcarrying zone}, i={1…N})

With:

$$Number\ of\ items\ processed(t, putaway) = the\ number\ of\ items\ processed\ storage\ zone\ (z)$$

(z= storage zone: 1: red box, 2: euro-pallet, 3: steel pallet, 4: self-carrying)

How to measure:
We can measure the number of items that are received, accepted, and put away in the storage zones with data from the ERP system. Since there is no match with the employee and the workstation he/she is working at for the accepting and put-away process, there is no information of which employee corresponds to what throughput measure.

Frequency of evaluation:
Once every 15 minutes.

How to react:
When there is a low throughput compared with the number of items in queue at a process may indicate a disturbance in the process. There is a need to look into this disturbance and find an explanation.

4.3.2 Performance indicators for the warehouse activities

In this section, we define the performance indicators that give insight in the warehouse activities.

VI. Performance indicator: Dock-to-stock time

Description:
The dock-to-stock time gives insight into the inbound process of the warehouse. It measures the time it takes from the moment an item arrive at the warehouse till it placed into a storage location. VMI Holland wants to put their items within 8 working hours into a storage location. When items are not placed on time into a storage locations, they cannot be picked. Therefore, a high dock-to-stock time can cause incomplete production orders, resulting in additional work finding these items in the previous stages, or result incomplete delivery production.

Measurement method*:*
From the moment item *i* arrive at the docking stage of the warehouse till the moment the item is placed into its storage location at time *t*.

Formula:

$$Average\ dock\ to\ stock\ time = \frac{\sum_{i=1}^{N} dock\ to\ stock\ time\ item(i)}{N}$$

$$Dock\ to\ stock\ time\ item(i) = putaway\ time(t) - \ arrival\ time\ (t)$$

Norm:
Maximum of 8 working hours.

How to measure:
Currently there is no registration of the time items arrive at the docking station of the warehouse. There is only insight into the point of time items are registered in the system. Currently, there is no way available to measure the exactly inbound time of an item. To measure the dock to stock time each item should have a unique identification number, such that it can be tracked throughout all warehouse processes.

Frequency of evaluation:
At the end of the day.

How to react:
When a high dock-to-stock time is observed, the foreman should increase the capacity in order to reach the norm of 8 working hours. When there is a structural high dock-to-stock time, the head of material management should investigate if there is a need for investment to increase the maximum capacity of workstations or redesign the process to achieve a higher efficiency rate.

VII. Performance indicator: Receiving time

Description:

The receiving time at the VMI Holland warehouse is the time it takes to accept an item and includes the time to register the product and allocate to a transport carrier (accept item). Since we cannot measure the time items actually arrives at the dock of the warehouse, this indicator is calculated by the time an item is registered into the system, till they are accepted and ready to get stored. A high receiving time may indicate an inefficient acceptance method or shortage of capacity.

Measurement method:

Per item *i*: from the moment items arrive in the warehouse till they are booked into the system at time t.

Formula:

$$Receiving\ time\ (i) = item\ accepted(t) - item\ registered\ into\ the\ system\ (t)$$

(i= item or batch; t=time unit)

Norm:

Max 4 working hours.

How to measure:

The ERP system records the point in time items are registered and accepted. This data can be used to determine the receiving time of an item.

Frequency of evaluation:

Hourly.

How to react:

An increase of the receiving time during the day may indicate low capacity at the workstation(s). A foreman should increase the capacity of the workstation by shifting employees from other activities. A structural high value should trigger the foremen or the head of material management to investigate if the problem can be solved by an investment in capacity or to redesign the process to achieve a higher efficiency rate.

VIII. Performance indicator: Put away time

Description:

The put-away time measures the time it takes from the moment the articles are accepted till they are located at the designated storage location. This indicator measures the efficiency of the put-away process. A high put-away time can be a trigger to review the storage strategy/method.

Measurement method:

The put-away time per item *i*, per storage zone *z*, is the total time *t* it takes to put an item in its storage location from the moment they are received.

Formula:

$$Average\ put\ away\ time\ (i, z) = item\ located\ at\ storage\ location\ (t) - receiving\ time\ (t)$$

(i=1..N; z={red-box zone, euro pallet zone, steel pallet zone, self-carrying zone})

Norm:

Max 4 hours.

How to measure:
In the system there is no link between the accepting time and the put-away time mutations. There is a need for a unique ID-code for each item to determine the put-away time.

Frequency of evaluation:
Hourly.

How to react:
An increase of the put away time during the day may indicate low capacity at the workstation(s). A foreman should increase the capacity of the workstation by shifting employees from other activities. A structural high value should trigger the foremen or the head of material management to investigate if the problem can be solved by an investment in capacity or to redesign the process to achieve a higher efficiency rate. According to the theory in Section 3.1, there are numerous options in the literature to increase efficiency and to reduce the put away time.

IX. Performance indicator: Order lead time

Description:
The order lead time gives insight into the outbound process of the warehouse. It measures the time from the moment an order placement till the shipment of that order. In the case of VMI Holland, the order placement is similar to the moment a desired pick-order has been released. The end time is determined by the time the truck leaves the warehouse to the production facility.

Measurement method:
Per production order *i*, the moment a desired pick date has been released, till the shipmen time.

Formula:

$$Order\ lead\ time = shipment\ time(i) - release\ time(i)$$

(i=1…N)

Norm:
Within 8 working hours.

How to measure:
The ERP system does not register the actual time the items leave the warehouse to the production facility. The ERP system does register the start date of a production order.

Frequency of evaluation:
At the end of the day.

How to react:
When the norm is structural not met may indicate that the release time of a production order is too soon or the capacity of the truck or in employees is too little. If the norm is not met, because of a missing item, the foremen should consider a quality improvement of the processes. Late deliveries of suppliers are not included in this performance measure, since the excess is not a result of an error of the warehouse activities.

X. Performance indicator: Storage accuracy

Description:
The storage accuracy measures the amount of orders that are complete at the first shipment. Incomplete production orders lead to additional activities that happen at the expense of the normal

warehouse activities. Besides, the incomplete production order can lead to incomplete production orders and delays in manufacturing. VMI Holland strives for an elimination of human errors.

Measurement method:
Per production order *i,* the number of incomplete orders as a fraction of the total production orders in a certain time window.

Formula:

$$Storage\ accuracy = \frac{number\ of\ incomplete\ production\ orders}{total\ number\ of\ production\ orders}$$

Norm:
0% (no missing items).

How to measure:
This fault is brought to light at the scanning tables, where a receipt is printed with the missing items.

Frequency of evaluation:
Daily.

How to react:
When there are a high number of errors, the foremen must identify the cause of these errors. There could be a technical issue or a structural problem at the put-away or good accept process. Employees could develop their competences in order to reduce the probability of a mistake.

XI. Performance indicator: Order picking time

Description:
The order picking time measures the time it takes to pick an entire production order. Since items are located in different storage zones, the end time of the pick process ends when the last item is picked from its storage location. The order picking time is influenced by the number of locations to be picked, the distance between these locations, and the processing speeds of employees. This indicator is part of the *order lead time* performance indicator. Since the size of a production order variates, a clear norm cannot be set.

Measurement method:
Per production order *i,* from the moment a picklist has been grabbed, till the entire list is picked.

Formula:

$$Order\ picking\ time\ (i) = \text{last item picked(i)} - \text{first item picked(i)}$$

Norm:
Max 4 hours.

How to measure:
The ERP system does register the picking times of individual items, but there is no clear report that links this information to the production order the item belongs to. Therefore there is a need to link these mutations to a pick time of an entire production order.

Frequency of evaluation:
Daily.

How to react:
An increase of the order pick time during the day may indicate insufficient capacity at the workstation(s). A foreman should increase the capacity of the workstation by shifting employees from other activities. A structural high value should trigger the foremen or the head of material management to investigate if the problem can be solved by an investment in capacity or to redesign the process to achieve a higher efficiency rate.

XII. Performance indicator: Shipping time

Description:
The shipping time indicates the time it takes between the moment items are picked and ready to get transported. At the VMI Holland warehouse, this moment includes the scanning process. The moment of shipment is set by the *work-preparation* department. A high shipping time may indicate congestion at the scanning tables or picks are performed to early.

Measurement method:
Per item, the time between picking and shipped away to the manufacturing facility.

Formula:

$$Shipping\ time(i) = shipment\ time\ (i) - end\ pick\ time\ (i)$$

(i= production order)

Norm:
Within the same day.

How to measure:
As same for the order lead time indicator, the date of shipment must be combined with the end time of the picking process in order to measure the shipping time.

Frequency of evaluation:
For each production order.

How to react:
If production orders are not transported the same day, because of a capacity restriction, the foremen should invest in an extra transportation truck. It may not happen that the materials for the production facility are delayed.

XIII. Performance indicator: Shipping accuracy

Description:
The shipping accuracy measures the completeness of production orders that pass through the scan tables. A high rate of failures indicates inaccuracies in the warehouse processes. Other than the storage accuracy this indicator measures the number of wrong articles of the production order. These items are not detected at the scanning tables, because the item number was correct, but the item number does not match the actual item. This can be caused when a wrong sticker is put on the item at the acceptance stage or at the supplier.

Measurement method:
The number of errors in production orders that are found during the scan procedure. This includes missing and wrong articles.

Formula:

$$Shipping\ accuracy = number\ of\ errors\ in\ production\ oders$$

Norm:
0 errors.

How to measure:
The logistic service team keeps track of errors in production orders that can easily be communicated with the foreman of the warehouse. Although, a clear report has to be developed.

Frequency of evaluation:
Daily.

How to react:
A high number of errors should triggers the foremen to investigate the accept stage, whether employees work according to the working protocols. If errors are caused by suppliers, the purchasing department should contact the supplier with feedback to indicate the problem.

4.4 The Enterprise Resource Planning system

With the information from the system, we are able to measure the throughput and utilization of storage zones, and the queue length/time of the accept stage.

4.5 Conclusion

In this chapter we identified the main stakeholders that influence or are influenced by the warehouse activities. Per stakeholder, we defined their stake and influence on the warehouse system. Thereafter, we combined the indicators found in the literature with the stakeholder analysis and checked if they satisfy the criteria of the S.M.A.R.T. principles. We selected 14 indicators and put them into a framework to get a clear overview. This framework is divided into three parts: general indicators, indicators for the warehouse activities, and indicators per storage zone. The framework enables the company to make decisions at the strategic, tactical, and operational level. We selected the following performance indicators: queueing time of processes, queue length of processes, workforce flexibility, throughput, dock-to-stock time, receiving time, put-away time, order lead time, storage accuracy, order picking time, shipping time, shipping accuracy, and on-time delivery. For each of these indicators, we gave a description, the measurement method, the formula, the norm, how to measure, how often, and how to react on the performance.

In the further chapters of the research, we analyse the performance of the inbound system of the warehouse with the help of a simulation model to find potential improvements. We focus on the inbound process of the warehouse, since these processes are exposed to the variation in workload.

5. Simulation model

In the previous chapter, we identified performance indicators that help VMI Holland to make decisions at the operational, tactical, and strategic level. In this chapter, we present a simulation model that will be used to determine the current and future performance of the inbound processes of the warehouse and identify potential process improvements. In Section 5.1, we explain why we use a simulation model to analyse and experiment with the performance of the system. In Section 5.2, we give the definition of a simulation model. In Section 5.3, we give the conceptual model of the simulation model. In Section 5.4, we determine the number of replications we need to perform for each intervention to get a reliable estimate. In Section 5.5 and Section 5.6, we verify and validate the model.

5.1 Ways to study a system

According to Law (2007), there are different ways in which a system might be studied, shown in Figure 5.1.

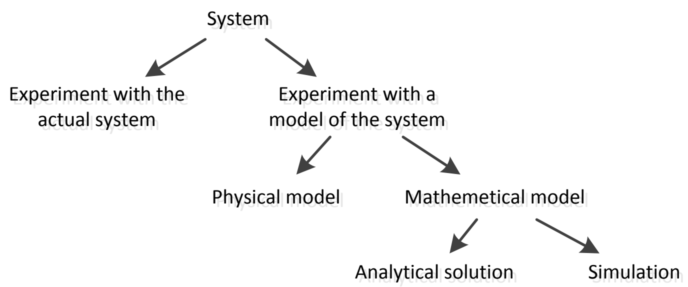

Figure 5.1: Different ways in which a system might be studies Law (2007)

Experimentation with the actual system is only possible when the experiment itself is not costly and does not disrupt the system. For this reason, it is usually necessary to build a model as a representation of the system. Whenever a model is build, the validity has to be analysed to make sure the model reflects the actual system. The researcher should now decide whether the model should be a physical model or a mathematical model. A physical model is useful to study engineering or management systems. A mathematical model represents a system in terms of logic and quantitative relationships that are changed to see how the model reacts. When a mathematical model is build and the system is simple, the solution might found using an analytic method. However, when the system is complex, the system must be studied by using a simulation.

In the case of VMI Holland, the processes within the current warehouse system are interconnected and subject to both variability and complexity. In order measure the performance of these interconnected processes and experiment with the system settings, it is hard to use an analytical approach or experiment with the actual system. Therefore, we make use of a simulation model.

5.2 Simulation model

In this section, we give the definition of a simulation model, which we use to analyse the different scenarios and interventions for the VMI Holland warehouse. First, we give the definition and characteristics of a simulation model. Second, we describe how we can create a model that gives an accurate representation of the actual system. Finally, we explain how we model the variability of the warehouse processes in the simulation model.

Definition and characteristics of the simulation model

Simulation can be defined as "*the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding behaviour of the system and/or evaluating various strategies for the operation of the system*" (Shannon, 1998). The terms *system* and *model* are key components of a simulation. A system can be defined as a collection of entities that interact with each other, e.g., employees or working stations and operate in time and space. A model is a simplified representation of the system to promote understanding of the real system. An important advantage of a simulation model is that management can test new designs and strategies without investing in the real system. Besides, simulation allows us to control time, in order to operate the system for several months, weeks, days, or hours. A drawback of simulation is that the gathering of reliable input data can be time consuming and the outcomes can be questionable (Shannon, 1998).

Terminology

A simulation model can either be deterministic or stochastic, static or dynamic, and discrete or continuous. A deterministic model does not contain probabilistic components and produces the same answer on each run. Stochastic models have at least some random input components, with outputs differ from run to run. A static model represents a system at a certain point in time. Dynamic models represent a change over time (Banks & Carson, 1984). Discrete simulation concerns the modelling of a system as it evolves over time in which the state variables change instantaneously at separate points in time. Continuous simulation concerns the modelling over time of a system by a representation in which the state variables change continuously with respect to time (Law, 2007).

Verification, validation, and creditability

According to Law (2007), we must validate and verify the model to determine whether a simulation model is an accurate representation of the actual system:

- Verification is concerned with the determining whether the simulation model meets a set of design specifications: “Have we built the model right?”
- Validation is the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study: “Have we built the right model?”

The final model and its results have credibility if the management accepts the model as ‘correct’. The process of verification, validation, and creditability during a simulation study is given in Figure 5.2.

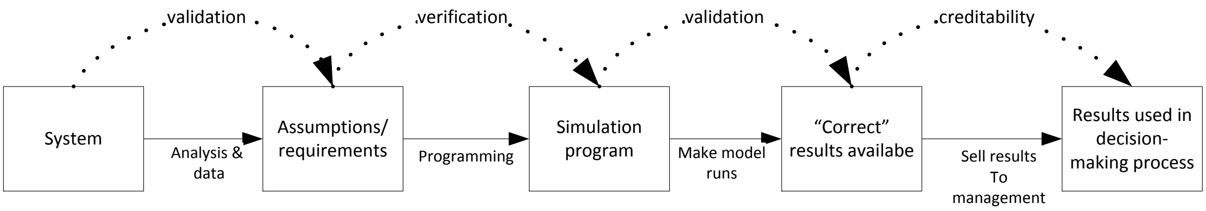

Figure 5.2: Verification, validation and creditability during a simulation study adapted from Law (2007)

Modelling variability and data collection

An important reason for using a simulation model is the ability to model variability. According to Robinson (2004), there are three options to represent variability:

i. *Traces:* a trace is a stream of historical data that describes a sequence of events including the times the events occur. The simulation simply reads the trace as it runs;
ii. *Empirical distributions*: an empirical distribution shows the frequency with which data values occur, represented by histograms or frequency charts. The data is commonly obtained from a trace. During a simulation run, values are sampled from the empirical distribution by using random numbers;
iii. *Statistical distributions:* statistical distributions are defined by a mathematical function or probability density function. There is no specific need to have data from the real system. A statistical distribution should give the full range of variability since it attempts to represent the total population variability instead of given data by an empirical distribution or trace. A well-defined approximation is necessary to represent the correct range of variability.

Selection of the theoretical distribution function (Law, 2007)
According to Law (2007) there are three steps in selecting the theoretical distribution function:

i. Hypothesizing families of distributions;
ii. Estimation of parameters;
iii. Determining how representative the fitted distributions are.

The first step of selecting a distribution function is to find what families (e.g., normal, exponential, uniform) appears to be appropriate, based on their shapes. The *summary statistics* provide information about the characteristics of the dataset: *minimum, maximum, mean, median, mode, variance, coefficient of variation, skewness,* and *kurtosis.* These values help suggesting an appropriate distribution family. A histogram can be used to get a graphical estimation of the dataset in order to identify the shape of the distribution function. The shape of the density should give a clue to the distribution that might be tried as a model for the data.

The second step in selecting the theoretical distribution function, estimates the parameters of the selected distribution.

The third step determines how well the hypothesized distribution functions represent the underlying data. In order to check the fit, a Quantile-Quantile plot (*Q-Q plot)* can be made and a *goodness-of-fit test can be performed*. If the estimated distribution function passes the tests, we know we have the right distribution function.

Approximate distributions
An approximate distribution, a type of statistical distribution, is commonly used to model variability in the absence of data. The simplest form of approximate distribution is the uniform distribution that is useful when only the most likely, minimum, and maximum value is known. The Triangular- and Beta distribution function is a more sophisticated approximation. The Triangular distribution function includes a third parameter, the mode, or most likely value. The Beta distribution function includes a third and fourth parameter, α and β that control the shape of the distribution.

5.3 Conceptual model

In this section, we give the conceptual model of the simulation model for the inbound process of the VMI Holland warehouse. The conceptual model is a description of the simulation model that we develop, describing the objectives, inputs, outputs, the model content, assumptions, and simplifications of the model. The simulation model of the warehouse process of VMI Holland can be described as a discrete event simulation. Since we are interested in the behaviour of the system over a particular period of time that starts and ends at a defined time, the simulation is a terminating simulation.

5.3.1 Objective

The objective of the simulation study is to measure performance indicators to determine the current performance of the inbound activities of the warehouse and to provide the management of VMI Holland with potential process improvements. This includes the understanding of the real world system and increase the efficiency of processes. The simulation helps understanding how the warehouse activities behave on decisions at the tactical and operational level before implementing it in practice. The outcomes of the model supports decisions whether to implement the decision or to reject it.

5.3.2 Inputs

The inputs of the model are those elements that can be altered to effect an improvement in, or better understanding of, the real world (Robinson, 2004). These inputs are depicted as the experimental factors of the simulation study. The input consists of both qualitative as well as quantitative factors. The model will be designed in such a way that we can enable the range of data input.

- The number of material inbound flow: increase or decrease of the material flow;
- Receive capacity: increase or decrease of capacity;
- Accept capacity: increase or decrease of capacity;
- Put-away capacity: increase or decrease of capacity;
- Number of workforce available: (may) differ in time;
- The use (or not) of a flexible workers pool: instead of a fixed position at a working station for each employee, we use with flexible workers that are able to work at multiple workstations.

5.3.3 Outputs

The output of the simulation model consists of *item specific* and *process specific* data. With the output data, we are able to measure the performance of the model when simulating the scenarios and interventions. The outcome of the simulation provides us with information on:

- The total amount of items processed;
- The dock to stock performance: the average dock to stock time of items and the number of items that are not processed within 8 hours;
- The receiving performance: the average waiting time of items at the receive stations and the number of items that are not accepted within 4 working hours;
- The put away performance: the average waiting time of items at the put away stations and the number of items that are not processed within 4 working hours;
- The productivity of working stations: the percentages of time that employees are occupied;
- The workforce: the number of used employees.

Analysing the output data helps to identify potential improvements of the system. Output data on workstation performance enables us identify bottlenecks at working stations. Output data on utilization indicates over or under capacity on working stations.

5.3.3 Model content

In this section, we present the components of the simulation model that enables us to transform the model inputs into outcomes. Here we clarify the scope of the model and the level of detail.

Scope

The scope of the model provides a link between the input factors and the outputs. Therefore, the model includes all the inbound activities that are needed to process an item within the warehouse and includes the: receiving stage, acceptance stage, and put-away stage. The source of the model consists of the delivery of items from suppliers and from the anonymous warehouse.

Level of detail

In the real world situation, the storage destination and storage policy of an item determines what workstations it passes within each stage of the warehouse. The storage destination (RB, EP, SP, or ZD) characteristic is determined by a probability according to a historical dataset. The storage policy (project based or anonymous policy) characteristic follows from the inbound trace. For each workstation, we define a distribution function to model the variability in the material flow. For each workstation, we define the processing time and occupation according to the workforce.

The number of items that flow into the system is based on a trace that corresponds to a historical dataset from April, 1st 2015 till July, 31st 2015. This trace of data contains the actual variability of the warehouse inbound flow.

Component list

The components of the simulation model are given in Table 5.1. This table includes all components of the simulation model that transfer the inputs into outcomes. This table gives the characteristics of the components. We selected a theoretical distribution function, as described in Section 5.2.

Table 5.1: Components of the simulation model.

Component	Information
Table: source of project based items	Trace of project based items, consisting the: arrival time of item, storage destination of item, batch size of arrival
Table: source of anonymous items	Trace of anonymous items, consisting: arrival time of item, storage destination of item, batch size of arrival
Workforce	Historical data of the occupation at workstations at each day
Shift calendar	Working hours of the simulation model according to the real world situation
Workstation: Receive	Processing time according to a lognormal distribution function with μ=XX and σ=XX in seconds
Workstation: Accept for RB and EP items	Processing time according to a lognormal distribution function with μ=XX and σ=XX in seconds
Workstation: Accept for SP and ZD items	Processing time according to a Beta distribution function with α=XX, β=XX, min=XX, and max=XX in seconds
Workstation: Put away RB	Processing time according to a Triangular distribution function with a=XX, b=XX, and c=XX in seconds
Workstation: Put away EP	Processing time according to a Triangular distribution function with a=XX, b=XX, and c=XX in seconds
Workstation: Put away SP	Processing time is included within the processing time at the accept station
Workstation: Put away ZD	Processing time is included within the processing time at the accept station

The processing time of the workstations is determined based on the available data from the ERP system. For the receive workstation and goods accept for RB/EP workstation, we use historical data from the ERP system to determine a theoretical distribution function. The distribution function of the processing time of the receive workstation fits a Lognormal function with a μ=XX and σ=XX. The distribution function of the processing time of the accept workstation for RB/EP items fits a Lognormal function with a μ=XX and σ=XX. Appendix D shows the Q-Q plot for both distribution functions that shows how well the sample data fits the theoretical distribution functions.

For the accept workstation for SP/ZD items and the put away station, there is an absence of data. Therefore, we make use of approximation distribution functions. To determine these functions, we discuss with employees the characteristics of the processing times and determine the parameters of the Beta and Triangular distribution function. We ask employees to give the absolute minimum and maximum value of the processing time. Thereafter, we discuss the shape of the distribution of the processing time with examples of shapes provided with explanations.

The processing time of the accept workstation for SP/ZD items follows a Beta function with α_1=XX and α_2=XX and a minimum processing time of XX seconds and a maximum of XX seconds.

The processing time of the put away workstation for RB items follows a triangular distribution function, with a minimum of XX seconds, a maximum of XX seconds, and a mode of XX seconds.

The processing time of the put away workstation for EP items follows a triangular distribution function, with a minimum of XX seconds, a maximum of XX seconds, and a mode of XX seconds.

Flowchart of model content

Figure 5.3 shows the flowchart of the simulation model and includes all components of Table 5.1.

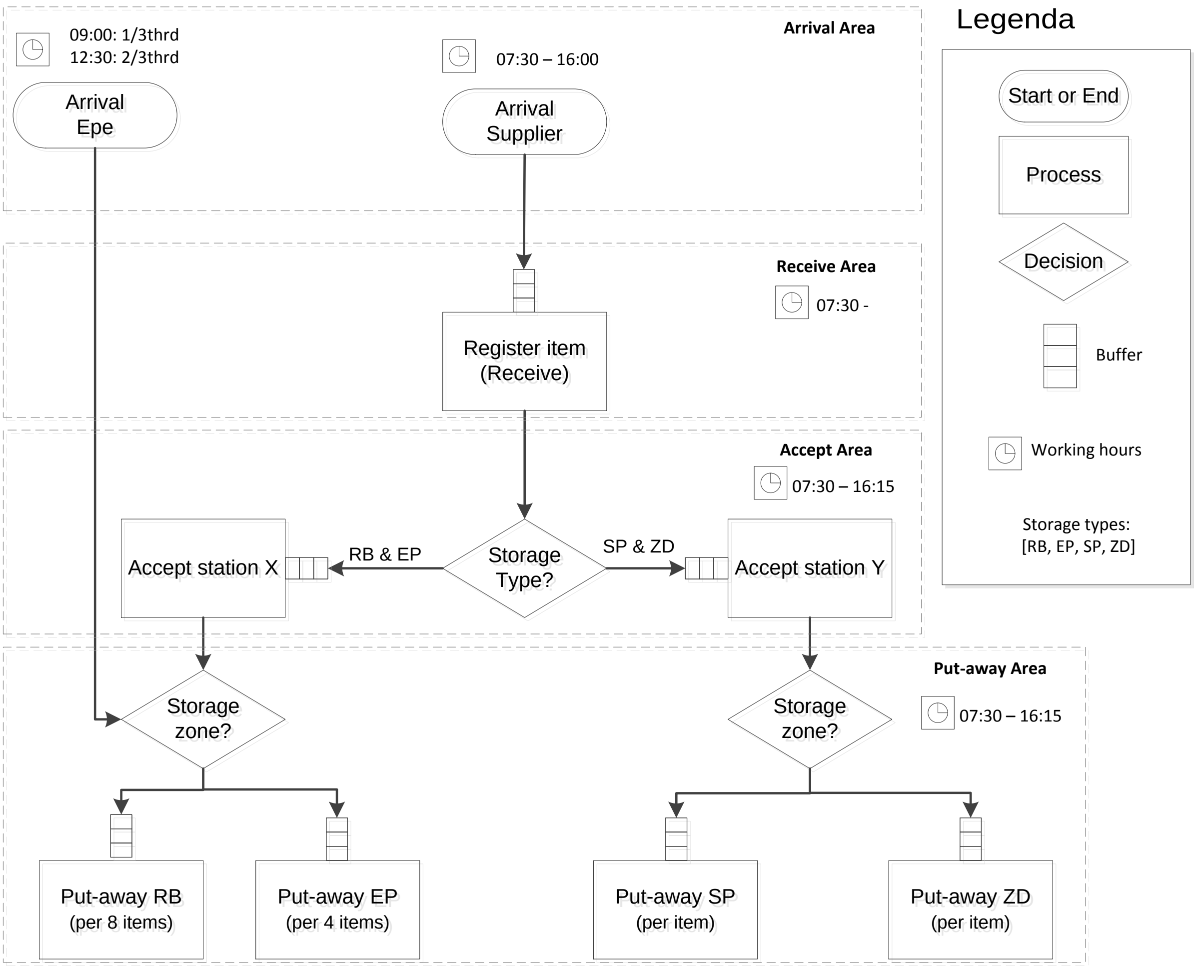

Figure 5.3: Flowchart of the material of the simulation model of the VMI Holland inbound process.

Type of materials

We define two different items: *anonymous* items, that arrive from the anonymous warehouse and *project* items that are delivered directly from the suppliers. Both items have their own source and enter the system according to their trace. Project-based items move through all the simulation stages, whereas the anonymous items only move through the put away area after they are generated. Table 5.2 gives the attributes of an item with the value type, and a description of the attribute.

Table 5.2: Attributes of the items that move through the simulation model

Attribute of item	Value Type	Description
Identification number	Integer	To keep track of items in data tables
Item name	String	Either *project-based* or *anonymous* for selection procedures
Storage destination	String	*{RB, EP, SP, ZD}* for selection procedures
Processing time receive	Time	Processing time according to the receive station's distribution function
Processing time accept	Time	Processing time according to the accept station's distribution function, based on the storage destination
Processing time put away	Time	Processing time according to the put away station's distribution function, based on the storage destination

Logically, anonymous items do not have a processing time for the receive and accept stage since they enter the system at the put away stage. The storage destination of items is determined by a trace according to current situation. For anonymous items applies: P(RB)=0.90 and P(EP)=0.10. For project-based items the following probabilities are used: P(RB)=0.75, P(EP)=0.18, P(SP)=0.03, and P(ZD)=0.04).

Decisions

For each workstation within a stage, the following conditions apply:

- Project-based items need to pass all stages of the warehouse and get processed at the workstation according to the storage destination they belong to;
- Anonymous items pass the put away stage of the warehouse and get processed at the workstation according to the storage destination they belong to;
- Processes at each working station follow a first come, first serve policy;
- An item can only move from the buffer to its workstation, when there is at least one item in the buffer and the occupation of the workstation does not exceeds its capacity;
- Items can only be processed at a stage within their time window. An item is not processed, when its processing time exceeds this window;
- Items from the acceptance station X move to the put-away stage every 15 minutes or when there lie respectively 64 or 10 items for the red box or euro pallet zone.

5.3.4 Assumptions and simplifications

- Overtime is not allowed. Except for the receive process, where all items have to be registered within the same day as their arrival;
- All items that are not processed by the end of the day are processed the day after;
- Items that arrive from the same supplier enter the system as a batch;
- All buffers in front of processes have an infinitive capacity;
- The capacity of a process is fixed and determined by the workforce of that day;
- The number of items that arrive from the anonymous warehouse correspond to the number of put-away actions that have to be performed. Some items with a similar storage destination are put on the same transporter and are put-away at the same time.
- The processing time of items at the small/medium acceptance station depends on the number of employees at the station. The distribution function of the processing time is based on an occupation of 4 employees. The processing time in the model is proportional to the number of employees;
- We neglect the walking distance between the workstations within the stages.

5.4 The number of replications

The run length of the model is 83 days, which corresponds to the historical data input of the material flow. To perform a statistical analysis for terminating simulations, we have to perform independent replications.

A replication is a simulation run that uses specific streams of random numbers (Robinson, 2004). The simulation model transforms the stochastic input to stochastic output causing inaccurate point estimates. Using multiple replications (i.e., runs with different random numbers), ensures that enough output data will be obtained from the simulation to estimate the model performance with sufficient accuracy. Each replication has the same initial condition but uses different random numbers.

We use the confidence interval method to determine the number of replications for the simulation model. The narrower the interval the more accurate the estimate is. The confidence interval is calculated with the formula:

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

Where:

$\bar{X} =$ mean of the output data from replications

$\bar{X}_i =$ the result from replication i

$S_n =$ standard deviation of the output data from *n* replications

$n =$ number of replications

$t_{n-1,\alpha/2}$ = value from Student's t-distribution with n-1 degrees of freedom and a significance level of α/2

We perform replications, until the width of the confidence interval, relative to the average, is sufficiently small. The number of replications is selected at the point where the interval reaches and remains below a 5% level of deviation. In formula:

$$n = \min\{\, i \geq n\colon \frac{t_{i-1,1-\alpha/2}\sqrt{\frac{s_n^2}{i}}}{|\bar{X}_n|} \leq \frac{\gamma}{1+\gamma}\} \quad (2)$$

Where,

$i = replication\ number$

$n = smallest\ i\ for\ which\ the\ fomula\ applies$

$\gamma = relative\ error$

For each model output, we calculate the smallest *i* for which formula (2) applies and take the maximum value for the simulation model. We find a maximum number of replications of 13.

5.5 Model verification

Verification is concerned with determining whether the conceptual model has been correctly translated into the computer model. In order to do so, we eliminate the errors that occur in the system during pilot runs by a structured walk-through of the program. Next, we run the simulation under a variety of settings of the input parameters and analyse the outputs. For the simulation model of VMI Holland, it is important that the output data of the model is correct. We check the distribution functions by plotting the data in a graph and re-calculate the parameters. Errors are rectified, resulting in a correctly translated computer model.

5.6 Model validation

For model validation, we use pilot runs to compare the outcomes with the existing system. Since there is a lack of high quality data of the existing system, we analyse the outcomes from pilot runs with the stakeholders that work closely in the system. Besides, we use the data that is available from the ERP to compare with the simulation outcomes. After presenting the model to several employees with high knowledge of the system, the model seems valid. The pilot runs we made seem to reflect the real world situation accurately.

6. Scenarios and interventions

In this chapter, we describe two scenarios and various interventions that help us to find potential improvements of the inbound processes of the warehouse. In the Section 6.1, we describe the first scenario. In Section 6.2, we describe the second scenario. For each scenario, we describe the interventions that will help finding potential improvements of the system.

6.1 Scenario I: Simulating the current situation

The first scenario represents the warehouse inbound system according to historical settings. Here, we simulate the actual inbound flow of materials according to a historical trace. Also, the workforce planning that determines the capacities of the workstations is set according to a historical trace. With the outcomes of the simulation, we are able to determine the performance of the system. We analyse the outcomes of the simulation run to identify disruptions in the system and to find potential process improvements.

6.1.1 Intervention I.1: Flexible workforce

In the first intervention, we seek for potential process improvements by the way of flexible workers. To deal with variation in workload, the company could increase the capacity with the available workforce. Here, a workers can work on all workstations within their own warehouse stage (receive, accept, and put away), e.g., employees that are planned for the accept workstation for RB/EP items, can also work on the accept workstations for SP/ZD items. For the simulation, we merge the workforce available per stage of the warehouse. In the actual system, employees need limited training to work at other working stations within their stage. Besides, the walking distance to the other workstation within the stage is minimal. To model workload flexibility, we add new conditions to the model:

- An employee can only work at other workstations when there are no items in queue at its own workstation;
- An employee can only work at other workstations when there is a need for help;
- An employee always return to its initial workstation when the item is processed;
- The maximum capacity of a workstation cannot be exceeded.

6.1.2 Intervention I.2: All items arrive at the start of the day

In the second intervention, we analyse the behaviour of the model when suppliers deliver their items at the start of the day (07:30). This intervention eliminates the variation in the arrival times of the items at the warehouse and may improve the efficiency of the workstations and reduce the overtime at the receive stage. Although it is hard for VMI Holland to make such arrangements with suppliers, it may stimulate to company to improve the arrival times of suppliers.

6.2 Scenario II: Simulating an increased material flow

The second scenario represents the current warehouse system, but faces an increased material inbound flow. We multiply the historical inbound flow with a factor of 2 that is expected according to the head of material management. Since we want to foresee what processes may form a bottleneck in the system, we set all workstation capacities to their maximum. In this scenario, we cannot simulate a flexible workforce, since all capacities of the workstations are already set to their maximums.

With the outcomes of the simulation, we are able to determine the performance of the system with increased workload. We analyse the outcomes of the simulation run to identify bottlenecks in the system and to find potential process improvements.

6.2.1 Intervention II.1: Increase capacity of bottleneck station

In the first intervention, we seek for potential improvements by increasing the maximum capacity of the workstations that form a bottleneck in the system. To find the desired performance of the system, we perform a stepwise approach. At each step, we analyse the performance of the system and increase the maximum capacity of the bottleneck workstation. We stop the stepwise approach when at least 99% of the items are placed within 8 working hours, as desired by the head of material management, into their storage locations. After each iteration, we analyse the outcomes of the simulation and increase the maximum capacities of the workstation that has highest waiting time. With the result of this intervention, we can recommend what investments should be made to handle an increase of the material flow.

6.2.2 Intervention II.2: No materials from the anonymous warehouse

In the second intervention, we analyse the behaviour of the model when there is no inbound material flow from the anonymous warehouse. This intervention is requested by the head of material management. It might be the case that in a future situation, there arrive no items from the anonymous warehouse. In this situation, there are almost 30% less items that have to be put away into a storage destination. To model this intervention, we simply eliminate the material flow from the anonymous warehouse.

6.2.3 Intervention II.3: All items arrive at the start of the day

Just as intervention I.2, we analyse the behaviour of the model when suppliers deliver their items at the start of the day (07:30). This intervention eliminates the variation in the arrival times of the items at the warehouse and may improve the efficiency of the workstations and reduce the overtime of the receive workstation. Although it is hard for VMI Holland to make such arrangements with suppliers, it may stimulate the company to improve the arrival times of suppliers.

7. Result from the simulation

In this chapter, we present the results from the simulation study. For each scenario and intervention, we analyse the outcomes of the simulation and provide explanations on the performance. In Section 7.1, we give the results from scenario I. In Section 7.2, we give the results from scenario II. Finally, in Section 7.3, we give the conclusion of the results.

7.1 Outcomes of scenario I: historical material flow

The results of the scenario I are not available in the public version of this report.

7.1.1 Intervention I.1: Flexible workforce

The results of intervention 1 of scenario I are not available in the public version of this report.

7.1.2 Intervention I.2: All items arrive at the start of the day

The results of intervention 2 of scenario I are not available in the public version of this report.

When all items arrive at the start of the day, there is a need for a large buffer to store all the items before they are received. If the items were delivered in a perfect time window, meaning there is no waiting time in front of the receive station, the performance of the system increases.

7.2 Outcomes of scenario II: increased material flow

The results of scenario II are not available in the public version of this report.

In the situation of an increased material flow, VMI Holland should make investments to increase the maximum capacity of workstations to increase the throughput and decrease the waiting times of these workstations. This may prevent backlog in the system that causes a poor performance.

7.2.1 Intervention II.1: Increase capacity of bottleneck station

The results of intervention 1 of scenario II are not available in the public version of this report.

After 5 iterations, the simulation model meets the desired performance. Over 99% of the items are placed within 8 working into their storage locations. If we summarize the iterations, the company should invest in the following resources:

- Increase the maximum capacity of the accept workstation for RB/EP items, from 11 to 13 employees;
- Increase the maximum capacity of the put away workstation for RB items, from 4 to 6 employees;
- Increase the maximum capacity of the put away workstation for EP items, from 3 to 4 employees.

The recommended expansion of the maximum capacities of the workstations ensures that, with the current variability in the material inbound flow, the company is able to process at least 99% of the items within 8 working hours. Appendix E visualizes the improvement on the maximum dock to stock time per day of the simulation. Here, we see that for most days the maximum dock to stock time lies far below the norm. The occupation rates of the workstations, shows that employees do not have work all the time. During the day there is no need to use the maximum capacity of a workstation. Using a flexible workforce will increase the efficiency per employee to let them work at multiple workstations.

In this situation, we need fewer employees for the same amount of work. Intervention 1 of scenario I confirms this statement.

7.2.2 Intervention II.2: No anonymous items

The results of intervention 2 of scenario II are not available in the public version of this report.

7.2.3 Intervention II2.3: All items arrive at the start of the day

The results of intervention 3 of scenario II are not available in the public version of this report.

7.3 Conclusion

The conclusion of this chapter is confidential. We do give some general results from the simulation outcomes.

Conclusions from (current) scenario I

In order to deal with the variability in workload and to increase the performance of the system, we recommend the company to use a flexible workforce.

When all items arrive at the start of the day, there is a need for a large buffer to store all the items before they are received. If the items were delivered in a perfect time window, meaning there is no waiting time in front of the receive station, the performance of the system increases.

Conclusions from (future) scenario II

After 5 iterations, the simulation model meets the desired performance. Over 99% of the items are placed within 8 working into their storage locations. If we summarize the iterations, the company should invest in the following resources:

- Increase the maximum capacity of the accept workstation for RB/EP items, from 11 to 13 employees;
- Increase the maximum capacity of the put away workstation for RB items, from 4 to 6 employees;
- Increase the maximum capacity of the put away workstation for EP items, from 3 to 4 employees.

When we eliminate the anonymous items from the inbound, the average dock to stock time decreases. It would increase the performance of the system, but there will be a need to invest in the maximum capacity of the accept station for RB/EP items.

When all items arrive at the start of the day, there is again a need for a large buffer to store all the items before they are received. If the items were delivered in a perfect time window, meaning there is no waiting time in front of the receive station, we could say that the performance of the system has slightly increased.

8. Conclusion and recommendations

This last chapter of the report describes the conclusion and recommendations of this research. The goal of the research is to provide the management with improvements on the current warehouse processes to decrease variation in workload and improve process efficiency. In Section 8.1, we give the conclusion of the research. In Section 8.2, we give recommendations to the company. Finally, in Section 8.3, we give the limitations of the research.

8.1 Conclusion

The main question of this research is:
"*What is the current performance of the logistic processes of the VMI Holland warehouse, and how can we control and improve the efficiency and effectiveness of the internal processes, while maintaining or improving the quality of outbound?"*

To answer the main question, we have formulated several sub questions. We present per sub question the key findings.

- *What are the characteristics and parameters of the processes of the VMI Holland warehouse?*

This question is answered in Chapter 2. We described the current activities and material flows of the VMI Holland warehouse. We identified two material flows: from suppliers and from the anonymous warehouse. The warehouse of VMI Holland consists of several stages: the receive stage, the accept stage, the put away stage, the pick stage, and the transport stage. The accept stage is divided into a workstation for small/medium items and a workstation for large/heavy items. Each storage zone has its own put away process: red box zone, euro pallet zone, and a zone for steal pallets and self-carrying items. The transport stage consists of a workstation for final control and a workstation for transportation. We have identified, with the help of data and measurements, the average processing time of the workstations. For the inbound processes, it is hard to foresee the workload due to the variability in arrival times and the discrepancy of expected and actual received items. The workload of the outbound process can be predicted accurately. It is of great importance that items are placed on time into their storage locations to prevent delays in the outbound process and at the manufacturing department. We conclude that the company is limited in controlling its processes due to a lack of performance measurements.

- *What are the performance indicators of general warehouse processes?*

This question is answered in Chapter 3. First, we studied the definition of the warehouse function with theory from literature. We identified three important functions of warehouses: (i) to bridge the interval of time between the moment that items are received and the moment that they are needed, (ii) to change the composition of the goods, and (iii) to guide items to their destinations. With a literature study, we clarified the importance of performance measurement and gave characteristics of proper performance indicators. We created a list of indicators that is commonly used in a warehouse environment. The list includes direct and indirect indicators that describe the utilization, productivity, and effectiveness of processes. The list can be found in Appendix C.

- *What performance indicators fit the needs of the stakeholders of the VMI Holland warehouse?*

This question is answered in Chapter 4. To select relevant indicators, we identified the main stakeholders of the warehouse activities. Two important stakeholders are the head of material management that wants to control the processes at the strategic and tactical level, and the foremen that want to control the processes at the tactical and operational level. We selected 14 indicators and put them in a framework: *The performance wareHouse of VMI Holland*. This framework gives a clear overview of the performance of the warehouse and allows direct adjustments on the performance. We selected the following performance indicators:

- Storage utilization;
- Queueing time of processes;
- Queueing length of processes;
- Workforce flexibility;
- Throughput;
- Dock to stock time;
- Receiving time;
- Put away time;
- Order lead time;
- Storage accuracy;
- Order picking time;
- Shipping time;
- Shipping accuracy;
- On-time delivery.

For each of these indicators, we gave a description, the measurement method, the formula, the norm, a description of how to measure, how often, and how to react on the performance.

- *How can we analyse the inbound process of the VMI Holland warehouse?*

This question is answered in Chapter 5. In order to find potential improvements for the inbound process of the system, we analysed the system with a simulation model. We translated the actual system into a conceptual model that includes the objectives, inputs, outputs, the model content, assumptions, and simplifications of the model. To model variability, we determined the theoretical distribution functions of workstations, properties of material types, arrival times, and the workforce. We built, validated, and verified the model in Siemens Plant Simulation. In order to create representative outcomes, each simulation will run for 83 days and consist of 13 replications. The outcome of the simulation provides information on the: dock to stock time of items, average waiting times of processes, and the occupation rates of the workstations.

- *What are the scenarios and interventions for the simulation model of VMI Holland?*

This question is answered in Chapter 6. We defined two scenarios, each having several interventions. For each scenario and intervention, we described the adjustments on the simulation model. Scenario I represents the current situation of the inbound process of the VMI Holland warehouse. To find potential improvements on the current system, we defined three interventions. The first intervention describes the current system with a flexible workforce, where employees are able to work on workstations within their warehouse stage. This intervention enables us to analyse the effects of a flexible workforce on the variability of workload. The second intervention describes the current system with an inbound flow that arrives at the start of the day. This intervention eliminates the variability of arrival times at the warehouse.

Scenario II represents a future situation of the inbound process of the VMI Holland warehouse. We defined a scenario where all capacities of the workstations are set to their maximum and where the inbound material flow will increase with a factor 2, as desired by the head of material management. To find potential improvements on the system, we defined two interventions. The first intervention consists of a stepwise approach to find potential improvements by increasing the maximum capacities of workstations. At each iteration, the maximum capacity of the bottleneck workstation will be increased till 99% of the items are placed within 8 working hours into their storage locations. The second intervention eliminates the material flow of the anonymous warehouse, as desired by the head of material management. The third intervention describes the current system with an inbound flow that arrives at the start of the day. This intervention eliminates the variability of arrival times at the warehouse.

- *How can VMI Holland improve their warehouse processes based on the results of experiments with various interventions and scenarios?*

This question is answered in Chapter 7. The outcomes of the simulation model are confidential. We do give some main findings.

Conclusions from (current) scenario I
In order to deal with the variability in workload and to increase the performance of the system, we recommend the company to use a flexible workforce.

When all items arrive at the start of the day, there is a need for a large buffer to store all the items before they are received. If the items were delivered in a perfect time window, meaning there is no waiting time in front of the receive station, the performance of the system increases.

Conclusions from (future) scenario II
After 5 iterations, the simulation model meets the desired performance. Over 99% of the items are placed within 8 working into their storage locations. If we summarize the iterations, the company should invest in the following resources:

- Increase the maximum capacity of the accept workstation for RB/EP items, from 11 to 13 employees;
- Increase the maximum capacity of the put away workstation for RB items, from 4 to 6 employees;
- Increase the maximum capacity of the put away workstation for EP items, from 3 to 4 employees.

When we eliminate the anonymous items from the inbound, the average dock to stock time decreases. It would increase the performance of the system, but there will be a need to invest in the maximum capacity of the accept station for RB/EP items.

When all items arrive at the start of the day, there is again a need for a large buffer to store all the items before they are received. If the items were delivered in a perfect time window, meaning there is no waiting time in front of the receive station, we could say that the performance of the system has slightly increased.

"*What is the current performance of the logistic processes of the VMI Holland warehouse, and how can we control and improve the efficiency and effectiveness of the internal processes, while maintaining or improving the quality of outbound?"*

VMI Holland is limited in measuring and controlling the performance of the warehouse processes. Therefore, we proposed a framework of performance indicators that enables the company to control its processes and make decisions at the strategic, tactical, and operational level. For each indicator we gave a comprehensive description that the foremen and head of material management can use to control their processes. The current system can be improved by implementing a flexible workforce consisting of employees that can work at several workstations at the time. Variation in workload can be reduced and backlog be prevented. In the future situation, the company should invest in the capacities of the accept workstation for RB/EP items and in the capacities of both the put away workstations for RB and EP items.

8.2 Recommendations

In this section, we give the recommendations of the research. In Section 8.2.1, we give a roadmap including recommendations to performance improvement. In Section 8.2.2, we give additional recommendations.

8.2.1 Roadmap to process improvement

From the results of the previous chapter, we identified the need for a flexible workforce and to increase capacities to control the variability in workload. In this section, we draft a roadmap that describes the steps the company should follow to successfully implement a flexible workforce and performance measurements to ensure the warehouse can manage its processes:

- Step 1: gain insight in performance of processes. To gain insight into the performance of the processes, we recommend VMI Holland to implement the Performance wareHouse of VMI Holland, as described in Section 4.2. This framework gives the company a clear overview and accurate insight in the performance of the warehouse activities. It enables the head of material management to make decisions at the strategic and tactical level and the foremen to adjust capacities at the operational level. The framework provides the foremen with the workload at processes and gives the waiting times. It prevents the processes from backlogs that can lead to a high dock to stock time. To measure all the indicators, adjustments on the current system has to be made:
    - i. Assign a unique identification number to items that arrive at the warehouse and keep track of which employee works on what workstation, using what scan device;
    - ii. Develop queries in the ERP that transforms data into working performance indicators that can be updated frequently;
- Step 2: design a flexible workforce. To control the variability in workload and to increase the efficiency of processes, we recommend VMI Holland to implement a flexible workforce, where employees can work at multiple workstations. We can subdivide this step into smaller milestones:
    - i. Identification of the recommended competences of each workstation;
    - ii. Document the competences of employees;
    - iii. Train employees if necessary.

  With this information, the foreman is aware of what person can work at which workstation making it easy to plan and shift employees. For each day, the foremen will need to compose a workforce with employees that have the right competences.
- Step 3: increase capacities. A temporarily increase of workforce at a certain workstations can only be achieved when the capacity of this workstation allows the increase. From the results of the simulation model of scenario II we have seen that when the material inbound flow increases, there is a need to expand the maximum capacities of workstations.
    - i. Increase the maximum capacity of the put away workstation for RB items from 11 to 13 employees. ;
    - ii. Increase the maximum capacity of the put away station for EP items from 4 to 6 employees;
    - iii. Increase the maximum capacity of the accept workstation for RB/EP items from 3 to 5 employees;
    - iv. Modify/simplify workstations in such way that employees can directly start working without set up times.
- Step 4: start managing the warehouse processes. With the framework of performance indicators and the ability to shift employees along workstations, the foremen are now able to react on variability in workload at the operational and tactical level. The head of material management is able to decision making at the tactical and strategic level.

The steps of the roadmap are shown in Table 8.1, along with the person/department responsible and the expected duration. All steps of the roadmap can be performed simultaneous, whereby the implementation can be realised within 10 weeks.

Table 8.1: Roadmap to process improvement.

Steps	Responsible	weeks
Step 1: Implement performance framework		**10**
1.1 Perform system adjustments for data collection	IT department	6
1.2 Construct queries to measure indicators	IT department	4
Step 2: Design a flexible workforce		**8**
2.1 Define recommended competences of workstations	Foremen	2
2.2 Documentation of employees competences	Foremen/Randstad	2
2.3 Train employees	Foremen	4
Step 3: Increase capacities		**7**
3.1 Increase capacity put away station RB items	Supply innovator	5
3.2 Increase capacity put away station EP items	Supply innovator	5
3.3 Increase capacity accept workstation RB/EP items	Supply innovator	5
3.4 Modify/simplify workstations to prevent setup times	Foremen	2
Step 4: Monitor the performance of the processes	Foremen / head of material management	**continuously**

Increasing the capacity of the put away workstation for RB items
During the research, we have seen that the maximum capacity of the put away station for RB items can be increased by preselecting items by the aisle they belong to. In this case, an additional employee sorts all items in the buffer in front of the put away station. Each employee that put away items into storage locations will be responsible for a subpart of the storage zone. An experiment in the actual system has proved this method.

Increasing the capacity of the put away workstation for EP items
We have seen that 29% of the processing time of the put away station for EP items consists of non-value adding proceedings (putting away empty euro pallets). We have also calculations showing that the efficiency of the put away stations will increase when the total number of items to put away at the time increases. A further research in this workstation might improve the efficiency of this workstation.

Increasing the capacity of the accept workstation for RB/EP items
The maximum capacity of the accept workstation for RB/EP items can easily increase by adding a new lane next to the existing lanes.

8.2.2 Additional recommendations

- We recommend VMI Holland to make use of the 'supportive' employees of the warehouse to temporarily increase the workforce and so the capacities of workstations;
- We recommend VMI Holland to improve the culture among employees within the warehouse. Currently, the warehouse functions as two separate islands;
- We recommend VMI Holland to prevent overtime of the receive station, by making arrangements with suppliers to deliver items in a tight time window, not and certainly not close to the afternoon;
- We recommend VMI Holland to develop workstations and equipment in such way that employees can immediately start working without losing time to start-up;
- We recommend VMI Holland to maintain or even improve the quality of the outbound, by letting employees work more often at other stages of the warehouse. We recommend to prepare (new) employees warehouse-wide, instead of a focus on a single stage;
- We recommend VMI Holland to reduce the amount of items that have to be processed from the anonymous warehouse. An analysis with the *supply innovation department* has proven that the workload of the put away station can be decreased by bundling items from the anonymous warehouse with the same production order (and so the same storage location). In this case, the workload from the anonymous workload can decrease with XX%.

8.3 Limitations

The research has several limitations that we discuss in this section.

- Data that is used for the inbound of items, is restricted to a particular period in time. The production of new innovative machines influences path items passes through the warehouse workstations;
- Due to a lack of information, approximation distribution functions have been used to determine the processing times of workstations. Although, these approximation distribution functions are obtained in the right way, they might differ from reality.

8.4 Further research

- Further research on the characteristics of processes and product types might improve the outcomes of the simulation, but asks for accurate performance measurement;
- Investigate the further possibilities for working with a flexible workforce to find the 'perfect' mix of employees that fit the desired competences of the workstations;
- A study to plan the arrival of items by suppliers in *perfect* time windows helps the company to prevent work in overtime at the receive station.

Bibliography

Aminoff, A., Kettunen, O., & Pajunen-Muhonen, H. (2002). Research on Factors Effecting Warehousing Efficiency. *International Journal of Logistics*, Vol. 5, No. 1. p.45-57.

Banks, J., & Carson, J. (1984). *Descrete-Event System Simulation.Prentice-Hall International Series in Industrial and Systems Engineering.* New Jersey: Prentice-Hall.

Caplice, C., & Sheffi, Y. (1994). A Review and Evaluation of Logistics Metrics. *The international journal of logistics management*, vol. 5, 11-28.

Carter, N. (1991). Learning to measure performance: The use of indicators in organisations. *Public administration*, vol. 69 Issue 1, p85-101.

De Koster, M., & Warffemius, P. (2005). American, Asian and Third-party International Warehouse Operations in Europe: A Performance Comparison. *International Journal of Operations & Production Management*, 25 (7–8): 762–780.

Dolgui, A., & Proth, J.-M. (2010). *Supply chain engineering: Useful methods and techniques.* London: Springer.

Freeman, R. E. (1984). *Strategic Management: A stakeholder approach.* Pitman: Boston.

Gelders, L. (1991). Production control in an 'engineer-to-order' environment. *Production planning and control*, 2, 280-285.

Gu, J., Goetschalckx, M., & McGinnis, L. F. (2006). Research on warehouse operation: A comprehensive review. *Elsevier*.

Gunasekaran, A. P. (2001). Performance measures and metrics in a supply chain environment. *International Journal of Operations & Production Management*, Vol. 21 Iss: 1/2, pp.71 - 87.

Hans, E., Van Houdenhoven, M., & Hulshof, P. (2012). A Framework for Healthcare Planning and Control. In R. Hall, *Handbook of Healthcare System Scheduling. International Series in Operations Research & Management Science, 168* (pp. 303-320). Berlin, Germany: Springer.

Hompel, M. t., & Schmidt, T. (2007). *Warehouse Management: Automation and Organisation of Warehouse and Order Picking Systems.* New York: Springer.

Kappauf, J., Lauterbach, B., & Koch, M. (2012). *Logistic Core Operations with SAP - Inventory Management, Warehousing, Transportation, and Compliance.* Germany: Springer.

Law, A. M. (2007). *Simulation Modeling & Analysis.* New York: McGraw-Hill.

Lorino, P. (2003). Méthodoes et pratiques de la performance. *Editions d'Organisation*.

Manzini, R. (2012). *Warehouseing in the Global Supply Chain: Advanced models, tools and applications for storage systems.* New York: Springer.

Mitchell, R., Agle, B., & Wood, D. (1997). Toward a theory of stakeholder identification and salience: defining the principle of who and what eally counts. *Academy of Management Review*, vol, 22. No.4, 853-886.

Robinson, S. (2004). *Simulation: The practice of model development and use.* Chichester: Wiley.

Rother, M. S. (1991). *Learning to See: Value Stream Mapping to Add Value and Eliminate Muda.* Brookline, MA: The Lean Enterprise Institute, Inc.

Rouwenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G., Mantel, R., & Zijm. (2000). Warehouse design and control: Framework and literature review. *European Journal of Operational Research*, Vol. 122, No. 3. p. 515-533.

Scheer, A.-W. J. (2006). *Corporate Performance Management: ARIS in Practice.* Germany: Springer.

Severance, A. (2011, March 19). *Warehouse management systems.* Opgeroepen op July 6, 2015, van H. Milton Stewart School of Industrial & Systems Engineering at Georgia Tech: https://www.isye.gatech.edu/

Shannon, R. E. (1998). Introduction to the art and science of simulation. *Proceedings of the 1998 Winter Simulation Conference*.

Staudt, F., Alpan, G., Di Mascolo, M., & Rodriguez, C. (2015). Warehouse performance measurement: a literature. *International Journal of Production Research*.

Appendices

Appendix A- Layout of the VMI Holland Warehouse

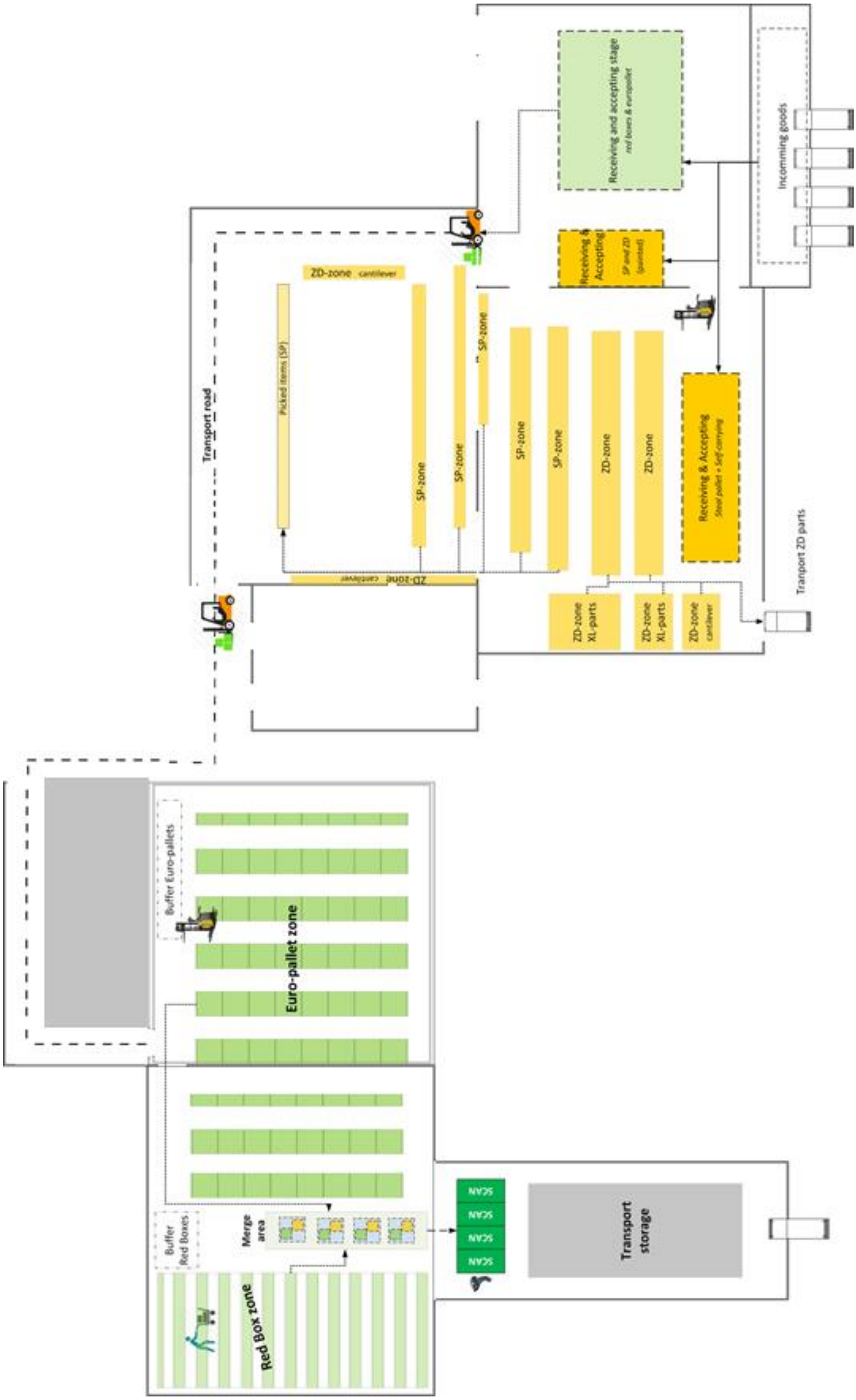

Figure A.1: Layout of the VMI Holland warehouse

Appendix B – Data registrations into the ERP system

Figure B.1 shows the data registrations of items into the ERP system, per activity of the warehouse.

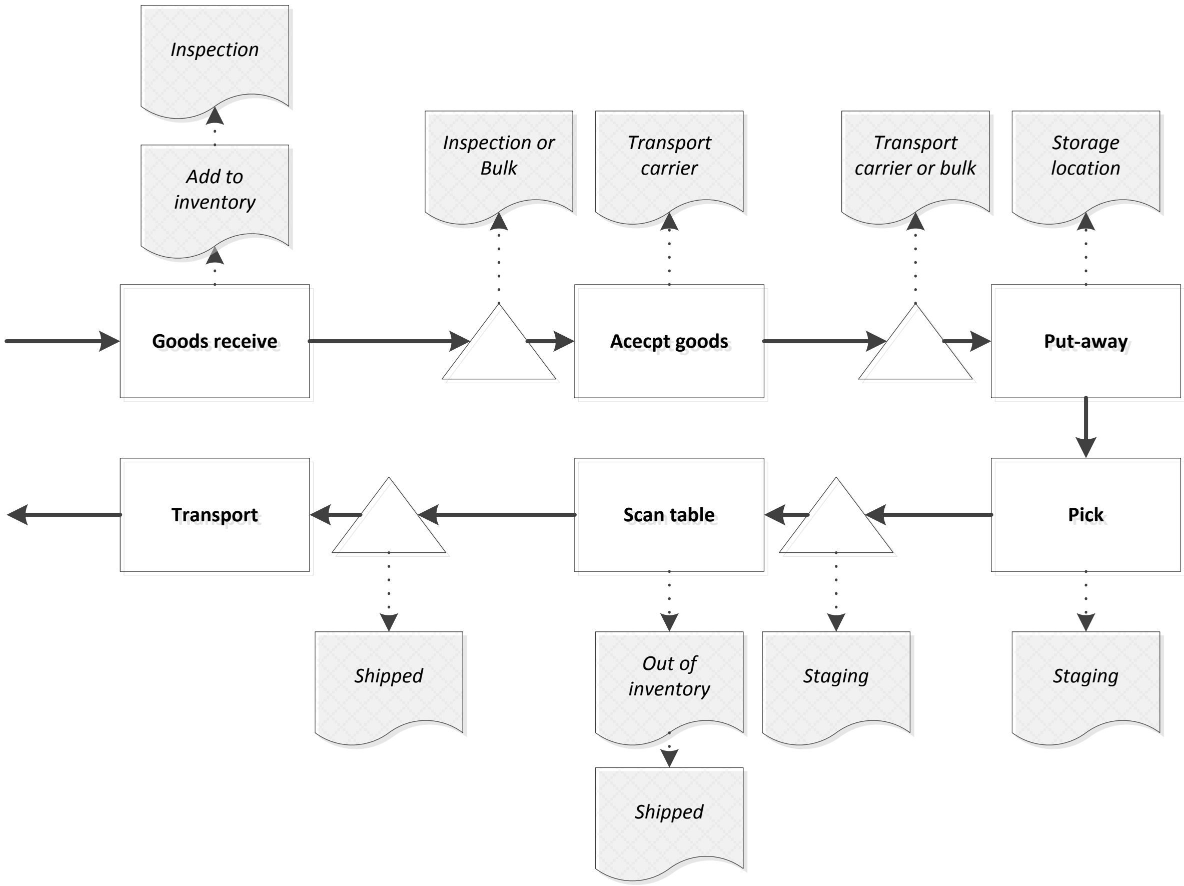

Figure B.1: Data registration of items into the ERP system, per activity of the warehouse.

Appendix C– Performance indicators from literature

Table C.1: Direct warehouse indicators according to Staudt et all. 2015

Dimensions	Indicator name	NP[a]
Time	Order lead time	9
	Receiving time	5
	Order picking time	4
	Delivery lead time	3
	Queuing time	2
	Puta way time	2
	Shipping time	2
	Dock-to-stock time	2
	Equipment time	1
Quality	On-time delivery	10
	Customer satisfaction	8
	Order fill rate	5
	Physical inventory accuracy	5
	Stock-out rate	4
	Storage accuracy	4
	Picking accuracy	3
	Shipping accuracy	2
	Delivery accuracy	2
	Perfect orders	2
	Scrap rate	2
	Orders shipped on time	1
	Cargo damage rate	1
Cost	Inventory cost	7
	Order processing cost	3
	Cost as % of sales	3
	Labour cost	2
	Distribution cost	2
	Maintenance cost	2
Productivity	Labour productivity	11
	Throughput	10
	Shipping productivity	7
	Transport utilisation	5
	Warehouse utilisation	4
	Picking productivity	3
	Inventory space utilisation	3
	Outbound space utilisation	3
	Receiving productivity	2
	Turnover	2

[a] Number of publications in literature

Table C.2: Indirect warehouse indicators according to Staudt et al. 2015

Indicator theme	NP[a]
Labour	7
Value-added logistics activities	4
Inventory management	4
Warehouse automation	4
Customer perception	3
Flexibility	3
Maintenance	1

[a] Number of publications in literature

Table C.3 Utilization, productivity, and effectiveness metrics according to Andersson et al. (1989)

Dimension	Example of metrics
Utilization	hours of machine used / machine capacity labour hour used / budgeted # of hours area of warehouse occupied / total area
Productivity	ton-miles deliver / cost incurred order processes / # hours of labour # pallets unloaded / hour of dock time
Effectiveness	# items filled / # items requested # of shipments on time / # shipments sent # of transactions error / # transactions

Appendix D - Q-Q plot distribution functions of Goods receive and Goods accept RB/EP

The quantile-quantile plot (Q-Q plot) is used to check how well a particular theoretical distribution fits the data. Figure D.1, shows the Q-Q plot of the processing time for the receive workstation. Figure D.2, shows the Q-Q plot of the distribution function for the processing time of the accept workstation for RB/EP items. As we can see, both datasets fits the proposed theoretical distribution functions quit well.

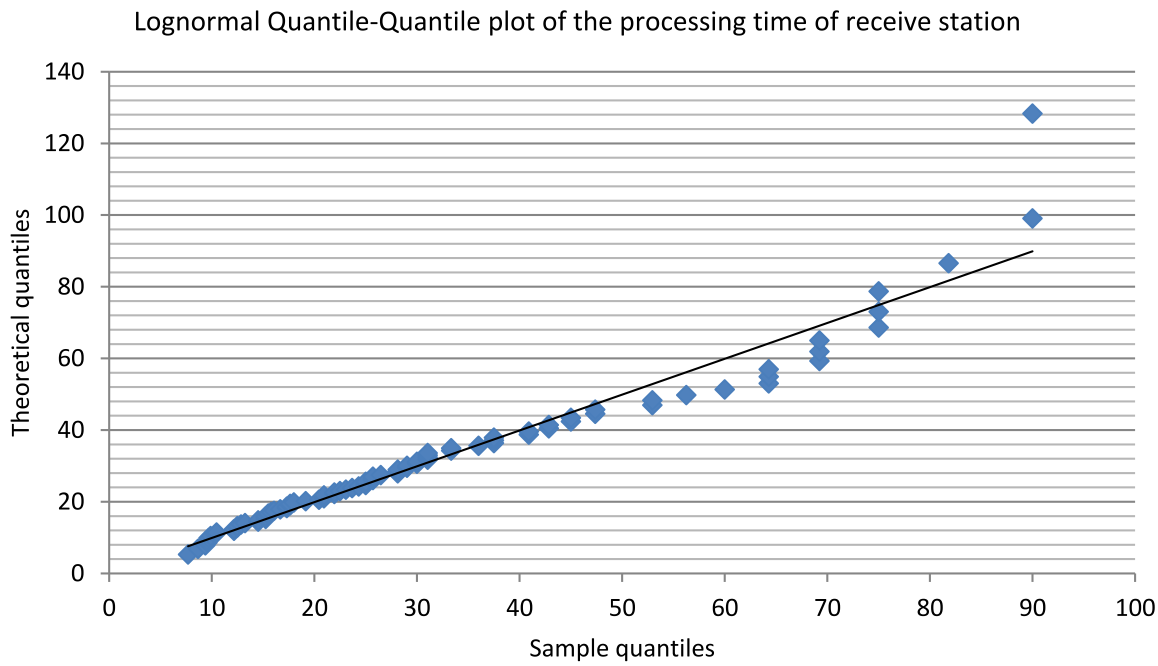

Figure D.1: Q-Q plot of the lognormal distribution function (μ=XX and σ=XX) of the goods receive processing time (n=89 items).

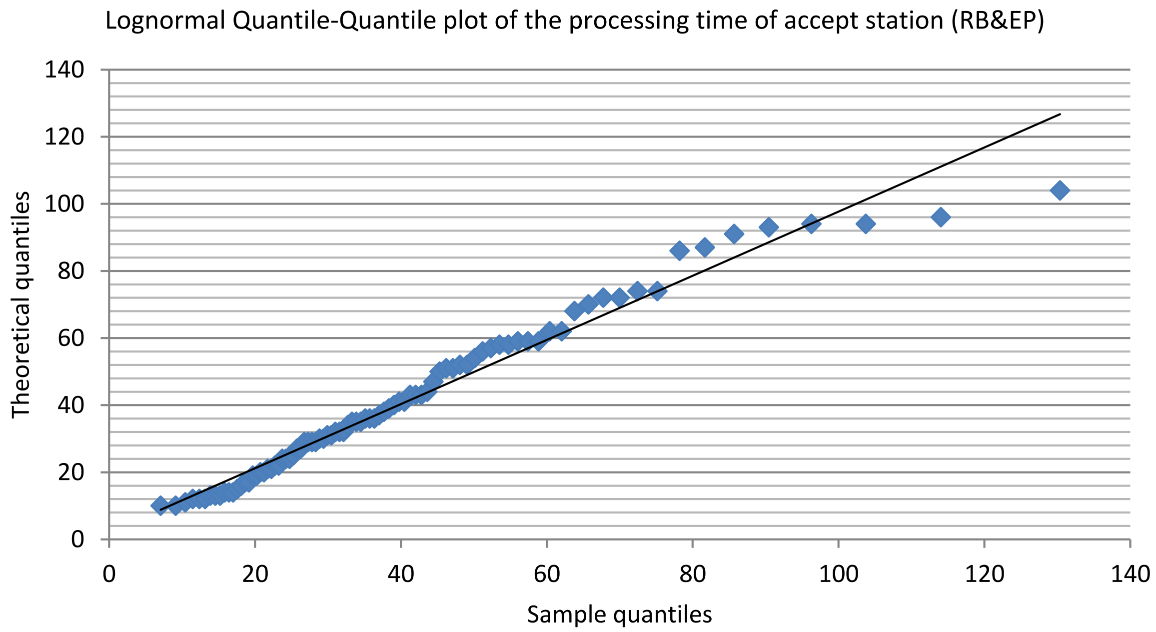

Figure D.2: Q-Q plot of the lognormal distribution function (μ=XX and σ=XX) of the goods accept RB/EP processing time (n=120 items).

Appendix E - Maximum dock to stock times of scenario II

Figures E.1 and E.2 show the maximum dock to stock time of items per day (blue dotted line) of the simulation against the desired norm (red line) and the total inbound items for that day (green column). The Y-axis on the left, correspond to the total number of inbound items and the Y-axis on the right correspond to the dock to stock time and the norm in hours. The values of the first figure correspond to the outcomes of the simulation of scenario II. The second figure shows the results after 5 iterations of the stepwise approach to find potential improvements on the model.

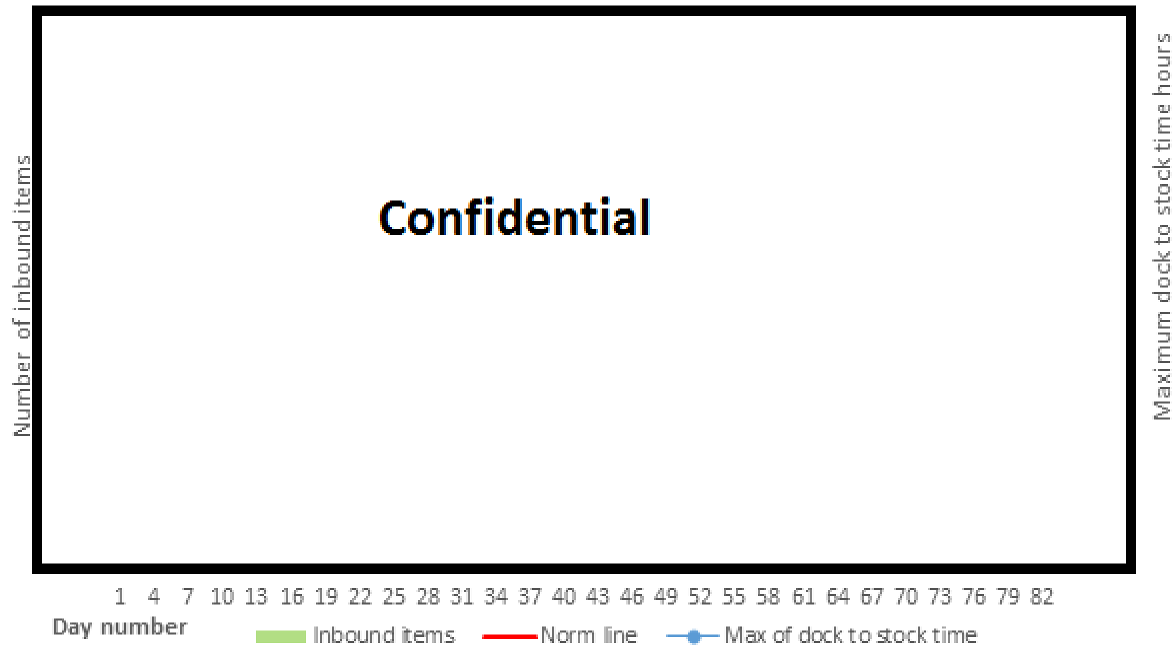

Figure E.1: The maximum dock to stock time per day plotted against the norm and total number of inbound items of scenario II.

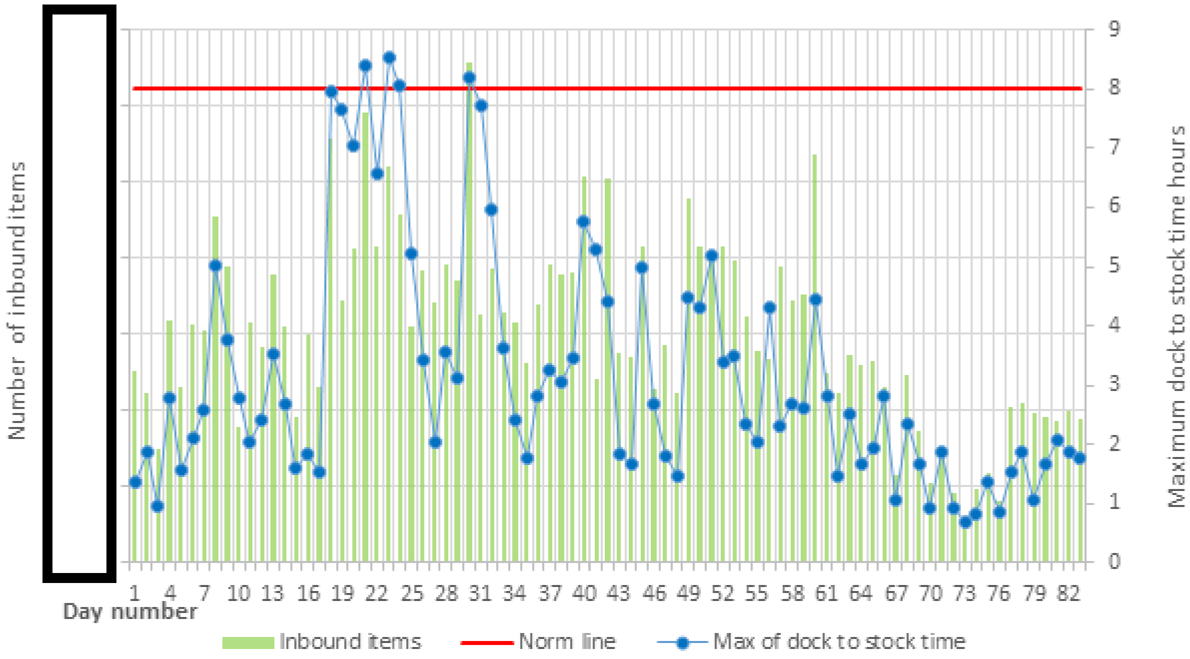

Figure E.2: The maximum dock to stock time per day plotted against the norm and total number of inbound items of scenario II after 5 iterations of improvements.

Appendix F - Outcomes of intervention 1, scenario II.

This information is confidential.