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Specialization:	Transport Engineering and Logistics
Report number:	2016.TEL.7998
Title:	**Simulation model for warehouse operation improvement through advanced WMS/Locating systems**
Author:	W.S. Romijn

Title (in Dutch)	Simulatie model voor verbetering van magazijn operaties met behulp van geavanceerd Warehouse management systeem met locatie bepaling.

Assignment:	Masters thesis
Confidential:	yes (until July 6, 2018)
Initiator (university):	prof.dr.ir. G. Lodewijks
Initiator (company):	drs. S. Merkx
Supervisor:	Dr. ir. H.P.M. Veeke
Date:	June 20, 2016

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Creditpoints (EC):	35
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Subject: **Simulation model for warehouse operation improvement through advanced WMS/Locating systems**

Nijman/Zeetank International Logistic Group is a logistics service provider that specializes in the transport of glass, petrochemicals, fuels, gasses and general cargo and also offers services for warehousing, handling and storage of containers, heating facilities, weigh bridge, drum filling and custom clearance activities. One of their operations is the internal logistics in a production plant for automotive glass of NSG Pilkington, one of the world's leading producers of glass.
To be able to keep up with the rising demand for efficiency, cost reduction, and the forecast of increased production coming from NSG Pilkington, Nijman/Zeetank looks to improve their warehouse operations by implementing an advanced Warehouse Management System (WMS) with locating capabilities.

Your assignment is to develop a decision support system that will help in making the decisions leading to the improvement of the warehouse operations. Studying relevant literature, developing the model, verification and validation of this model, application in a case study, presenting solid conclusions and recommendations and reporting the research work are all part of this assignment.

The report should comply with the guidelines of the section. Details can be found on the website.

The professor,

Prof.dr.ir. G. Lodewijks

Preface

This is the final report of my Master thesis titled 'Simulation model for warehouse operation improvement through advanced WMS/Locating systems' and the research was performed as the final part of my Masters program Transportation Engineering and Logistics at the faculty of Mechanical Engineering of Delft University of Technology. In this report I present my research on warehouse operations and it should give readers an insight on how these operations could be improved, focussing on the operations of Nijman/Zeetank in Chmielów. I was engaged in researching and writing this thesis from January to June 2016.

During the process of writing a number of people have contributed academically, practically or in support. First I would like to thank prof. dr. ir. G. Lodewijks, drs. S. Merkx and Mr. C. van Noordt as the initiators of this project. Each of you provided valuable insights in practical or academical areas which helped me in gaining a better insight in the subject at hand. Furthermore I would like to thank I. van der Zanden, my day-to-day supervisor at Mieloo & Alexander B.V., for the feedback sessions, insights and support during this research. I would like to thank dr. ir H.P.M. Veeke, who was my supervisor from the university, he guided me in the structure of the research and provided valuable handles for my work. Moreover my thanks go out to Michal Słuchocki for the cooperation and especcially to Rafal Drozdowski for all his time and dedicated effort during this project. Finally I would like to thank all my family and friends for being helpful and supportive during my time at the Delft University of Technology and during this final research.

Walter Romijn
Hoofddorp, the Netherlands
June 20, 2016

Summary

Nijman/Zeetank International Logistic Group is a logistics service provider that specializes in the transport of glass, petrochemicals, fuels, gasses and general cargo and also offers services for warehousing, handling and storage of containers, heating facilities, weigh bridge, drum filling and custom clearance activities. One of their operations is the internal logistics in a production plant for automotive glass of NSG Pilkington, one of the world's leading producers of glass. The responsibility of Nijman/Zeetank starts with the reception of raw glass, semi-finished and finished products from either inbound trucks or from the production lines. After receiving these products they are transferred to the warehouse and stored awaiting reprocessing or shipment to the customer. To be able to keep up with the rising demand for efficiency, cost reduction, and the forecast of an increased production coming from NSG Pilkington, Nijman/Zeetank looks to improve their warehouse operations by implementing an advanced Warehouse Management System (WMS) with locating capabilities.

In order to help the warehouse manager in his decisions regarding the utilisation of the available resources a decision support system is to be developed that will answer the main research question: *'How are the forklifts and storage area of Nijman/Zeetank in Chmielów to be used to meet the expected increase in demand from NSG Pilkington in an efficient and effective way?'*

With the WMS, the amount of real time information in the warehouse is increased and it is possible to track each individual Stock keeping unit (SKU). This creates the opportunity to change the storage policies in the warehouse. The first alternative is to keep the zones as they are but change the way SKUs are stored within them, the second alternative is to store everything as close to its destination as possible in order to try and reduce travel times and increase the flexibility for the deliveries. The last alternative is to store all SKUs close to their entry point to minimize the storage travel time. These three alternatives are tested in two separate cases using the decision support tool that has been developed.

For the first case the warehouse was simulated with the current throughput and the second case used the predicted future throughput. According to these simulations the warehouse in Chmielów is able to operate with just 7 forklifts under the current throughput and with 12 under the future throughput.

Following these results it can be concluded that the implementation of an advanced WMS will lead to savings regardless of the chosen storage policies. But with the Zones storage policy the largest savings potential is available.

Samenvatting

Nijman/Zeetank International Logistic Group is een logistiek service provider gespecialiseerd in het transport van glas, petrochemische producten, brandstoffen, diverse gassen en stukgoederen. Daarnaast biedt Nijman/Zeetank onder andere ook diensten aan voor het vervoer en opslag van tankcontainers, het inklaren van goederen bij de douane en de opslag van goederen in een warehouse. Eén tak van hun bedrijf is verantwoordelijk voor de interne logistiek in een productie faciliteit voor autoruiten van NSG Pilkington, één van de grootste glasproducenten in de wereld. De verantwoordelijkheid van Nijman/Zeetank begint bij de ontvangst van grondstoffen, half fabricaten en eindproducten van leveringen van vrachtwagens of vanuit de productielijnen. Na ontvangst worden deze vervoerd naar het magazijn waar deze worden opgeslagen in afwachting van verdere processen of verzending naar klanten. Om de groeiende vraag naar efficiëntie, kostenbesparing en het vooruitzicht van de groeiende productie van NSG Pilkington op te kunnen vangen, wil Nijman/Zeetank de operatie in het magazijn verbeteren door een geavanceerd WMS met locatie bepaling te implementeren.

Om de magazijn manager te helpen met het maken van beslissingen over het gebruik van de beschikbare middelen, moet een tool worden ontwikkeld welke de volgende hoofdvraag zal beantwoorden: *'Hoe moeten de heftrucks en opslagruimte van Nijman/Zeetank in Chmielów worden gebruikt om de verwachte groei in vraag van NSG Pilkington in een efficiënte en effectieve manier op te vangen?*

Door het implementeren van een WMS, groeit de hoeveelheid beschikbare informatie in het magazijn substantieel en is het mogelijk om elke individuele pallet te volgen. Met behulp van deze informatie kunnen de regels voor het opslaan van goederen worden veranderd. Het eerste alternatief is om de zones te houden zoals deze nu zijn, maar de manier waarop de pallets worden opgeslagen te veranderen, een tweede optie is om elke pallet zo dicht bij mogelijk bij zijn bestemming op te slaan, om de rijtijden van de heftrucks te verminderen en ondertussen de flexibiliteit voor de leveringen te waarborgen. Een laatste alternatief is om elke pallet zo dicht mogelijk bij het punt op te slaan waar deze binnen komen om de tijd die nodig is om het product op te slaan zo laag mogelijk te houden. Deze drie alternatieven zullen worden getest in twee verschillende cases met behulp van de ontwikkelde tool.

De eerste case gaat over het magazijn met de huidige doorstroom en de tweede case gebruikt de toekomstige doorstroom. Aan de hand van deze simulaties kan worden geconcludeerd dat Nijman/Zeetank het aantal heftrucks terug kan brengen van 14 naar 7 heftrucks met de huidige doorstroom en naar 12 heftrucks voor de toekomstige situatie.

Uit de resultaten van de cases kan worden geconcludeerd dat de implementatie van een geavanceerd WMS tot besparingen zal leiden, maar dat het grootste besparingspotentieel kan worden gerealiseerd met het eerste alternatief, het behouden van de zones.

List of Symbols

L	average number of elements in queue
W	waiting time in a queue
λ	mean response time
$\dot{n}_{performed}$	performed tasks per hour
$n_{performed}$	performed tasks
n_{task}	tasks
$T_{dead-head,i}$	time spent dead-heading by forklift i
$T_{elapsed}$	time elapsed
$T_{idle,i}$	idle time of forklift i
T_{idle}	total idle time
$T_{op,i}$	total operational time of forklift i
T_{op}	total operational time of all forklifts
$T_{servicetime,SKU}$	handling time for 1 SKU
$T_{work,i}$	working time of forklift i
T_{work}	total worked time
$\bar{T}_{servicetime,SKU}$	mean handling time for 1 SKU
$\bar{n}_{SKU}$	mean number of SKUs
$\bar{T}_{SKU}$	average time required for 1 SKU
$\bar{T}_{dead-head}$	total time spent dead-heading
$\bar{T}_{driving}$	average driving time for 1 SKU
$\bar{T}_{pick}$	average picking time
$\bar{T}_{put}$	average putting time
$\bar{s}_{driving}$	average driving distance for 1 SKU
n_{SKU}	SKUs
$n_{forklift}$	forklifts
$v_{forklift}$	forklift speed

List of Abbreviations

3PL	Third Party Logistics
AGR	aftermarket glass
BFIFO	Batch First-In, First-Out
BIP	Binary Integer Programming
COI	Cube-Per-Order Index
COL	Closest-Open-Location
DC	Distribution center
DED	Dedicated Storage
DOS	Duration of Stay
ERP	Enterprise resource planning
FIFO	First-In, First-Out
FOL	Farthest-Open-Location
I/O	Input/Output
IP	Integer Programming
KPI	Key Performance Indicator
LIFO	Last-In, First-Out
LOL	Longest-Open-Location
LP	Linear Programming

MIP	Mixed Integer Programming
OE	original equipment
RAN	Random Storage
RF	Radio Frequency
SKU	Stock keeping unit
SLAP	Storage Location Assignment Problem
SLAP/II	storage location assignment problem based on item information
SLAP/NI	storage location assignment problem based on no information
SLAP/PI	storage location assignment problem based on product information
TF	Transfer Zone
VAP	Vector Assignment Problem
WIP	work in process
WMS	Warehouse Management System

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 General Introduction

Due to globalisation the demand for new logistics solutions is growing every day, requiring faster and cheaper ways to ship items all across the globe. To meet this demand, global suppliers have to keep improving their operations in terms of delivery speed and cost.

These improvements range from the fuel economy of the ships to the speed of a conveyor belt. Each little part in the supply chain is examined to find all possibilities. All suppliers are responsible for a large number of different items, which are produced at different locations and are shipped to different destinations. Therefore each supplier will use certain hubs in its supply chain. At these hubs, different items are received, sometimes stored, sorted to their destination and shipped in all different combinations. One type of a hub is a warehouse, which is mostly serviced by trucks and handles every size of item that is requested.

Nijman/Zeetank International Logistic Group, with its headquarters in Spijkenisse, The Netherlands, is a logistics service provider that specializes in the transport of glass, petrochemicals, fuels, gasses and general cargo and also offers services for warehousing, handling and storage of containers, heating facilities, weigh bridge, drum filling and custom clearance activities.

One of the branches of Nijman/Zeetank is located in Poland and is responsible for the warehouse and distribution operations of the automotive glass plants of NSG Pilkington, one of the world's leading producers of glass. This branch operates in the city of Sandomierz and in the town of Chmielów. The responsibility of Nijman/Zeetank starts with the reception of raw glass, semi-finished and finished products from either inbound trucks or from the production lines. After receiving these products they are transferred to the warehouse and stored awaiting reprocessing or shipping to the customer. In order to be able to keep up with the rising demand for efficiency, cost reduction, and the forecast of increased production coming from NSG Pilkington, Nijman/Zeetank looks to improve their warehouse operations.

To assist with the improvement of the operations of Nijman/Zeetank, Mieloo & Alexander B.V. looks to develop a decision support system that is capable of showing the effects of different tactical decisions regarding the warehouse operations.

1.1.1 Structure of the Report

This report will start with a description of the current situation of the warehouse in Chmielów followed by an analysis, which covers the warehouse operations, the different levels of decision making in a warehouse and different types of decision support systems that can be used in the management of a warehouse. For the analysis of the warehouse in Chmielów a number of research questions are formulated which will be answered in the following chapters. The questions are:

1. What is the current situation in the warehouse of Nijman/Zeetank in Poland and why should it be improved?
2. What is warehousing?
3. How can the operational performance be measured?
4. What are the decisions made on the different levels (Strategic, Tactical, Operational)?
5. What kind of decision support system is most suited for this problem?

These questions will lead to the formulation of a research question, that will help in finding a fitting solution for the operations of Nijman/Zeetank in the warehouse (chapter 4). To answer this question a decision support tool will be developed to help the warehouse managers in the making of decisions.

Chapter 2

Current situation

The warehouse located in Chmielów is a Third Party Logistics (3PL) operation that handles the logistical operations in the unit-load warehouse of an automotive glass production plant. Here Nijman/Zeetank has to deal with a multitude of products moving through the warehouse in containers (figure 2.1), or Stock keeping unit (SKU), that can be categorized into four different types: raw material, work in process (WIP), original equipment (OE) and aftermarket glass (AGR). Both OE and AGR are finished products that are ready to be used by the end user and therefore when finished product is mentioned, both are implied.

Last year a new production line was finished, significantly increasing production. To be able to cope with this increase in product throughput, a new warehouse was built and taken into use. To be able to increase the quality and efficiency of the operations, Nijman/Zeetank is looking into the possibilities of implementing new technologies in the area of Warehouse Management Systems. This section will describe the system using a black box description and will zoom in to a lower level, to show a simple model of the warehouse. The goal is to find an answer to the question:

1. What is the current situation in the warehouse of Nijman/Zeetank in Poland and why should it be improved?

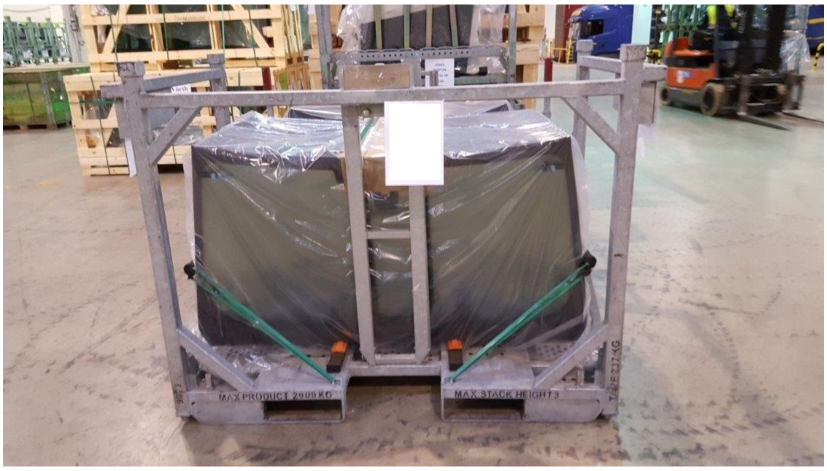

Figure 2.1. Unit load containers used in the warehouse

2.1 The role of Nijman/Zeetank

Nijman/Zeetank is responsible for all logistical operations in the production plant and delivers all warehousing services to NSG Pilkington in Chmielów. They receive product orders from NSG Pilkington and have to report back when orders are completed. Furthermore, Nijman/Zeetank is responsible for the transportation of SKUs with glass between the production plant in Sandomierz and Chmielów, a distance of just 25 km.

Nijman/Zeetank is operating as a reactive player in the supply chain, which means that they are completely in the dark about the organisation of NSG Pilkington. Besides, decisions about the amount of product produced is only communicated at the moment it arrives. Nijman/Zeetank has no other choice but to react to the amount of product moving in and decisions made by other departments.

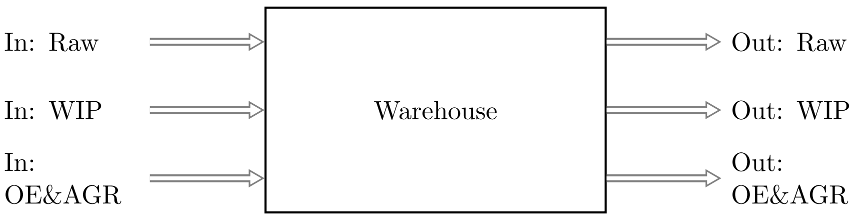

Figure 2.2. The warehouse of Nijman/Zeetank as a black box

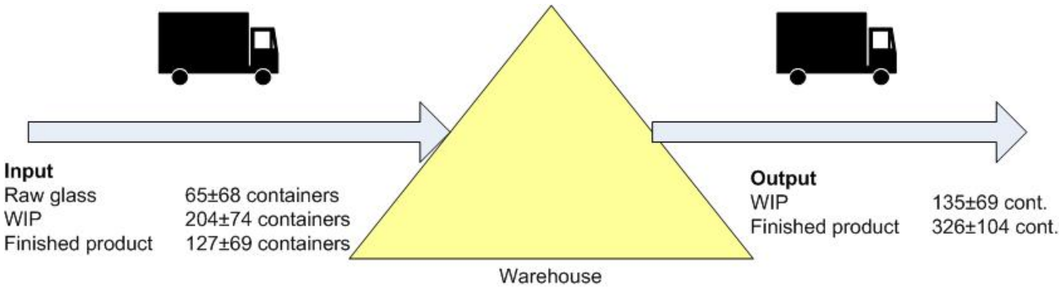

Figure 2.3. The warehouse of Nijman/Zeetank with in- and outbound trucks

2.2 Black box

Figure 2.2 shows the black box with the different flows and the combinations in which they arrive and leave the warehouse. As the system has the function to store SKUs of glass, figure 2.3 shows the black box as an inventory sign with its inputs and outputs per month. Over the year 2015 78% of all inbound trucks came from the production plant in Sandomierz. These trucks continuously move between the two plants to provide Chmielów with the required materials to continue production.

Input The input of the system is divided in three different categories, each with its own mean and standard deviation. With over 204±74 SKUs entering the warehouse each day, the largest inbound flow belongs to the WIP products. These SKUs are produced at other sites and are transported here to be further processed or combined and shipped to other production plants. The other inputs are the raw glass and the finished products that were produced elsewhere. The raw glass is delivered in either metal or wooden SKUs, where the wooden SKUs contain a larger amount of sheets as the metal SKUs.

Output The output of the system is divided in two separate flows, one for the WIP SKUs and one for the finished products. The WIP is transported to other production plants of NSG Pilkington to complete their production process and the finished products are shipped to the end consumers. Here the amount of finished products SKU shipped is more than double the amount of WIP products with 326±104 SKUs over 135±69 SKUs.

2.3 Simple model

When zooming in on the black box from figure 2.3 it is possible to add more information and gain a better insight in the workings of the system. This first simple model is shown in figure 2.4 and shows the flow of the products through the production facility. Three separate inbound flows of product are defined, each at a different position:

- Raw glass
- WIP glass
- Finished products

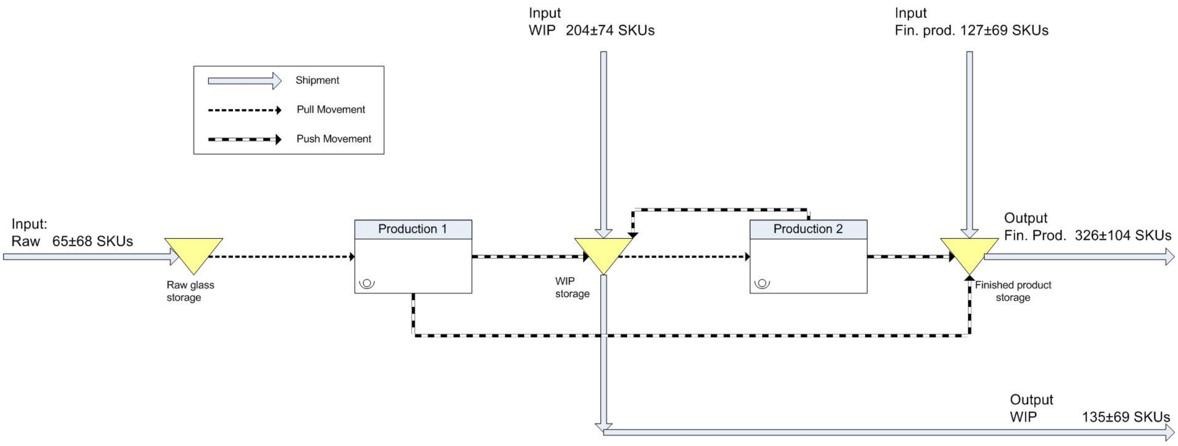

Figure 2.4. A simple model of the warehouse

2.4 Operations

To limit the number of handling errors, certain procedures are developed for handling the products, these can be found in appendix B. Most of the information is moved through the warehouse on paper, and changes in location or deliveries are signed of on order forms by hand and added to the Enterprise resource planning (ERP) later.

The warehouse is divided in a number of zones, where each zone is appointed to a type of product. Table 2.1 shows these zones, the number of storage bins and the type of products stored in that zone.

Zone	Storage bins	Product type
A	53	WIP for Production 2.A
C	204	WIP for Production 2.B
P	22	Repackaging
S	162	OE and AGR
W	93	Raw materials
Staging	22	Staging lanes for shipments

Table 2.1. Warehouse zones

To describe the current operations in the warehouse, they will be divided in the categories described in section 3.1.1 and will add another, Accumulation and Sorting.

2.4.1 Unload

Figure 2.2 shows three different flows of products moving into the warehouse, all of which need to be unloaded and added to the inventory of the warehouse. The first flow entering the warehouse is the product being delivered by truck for which the procedures are presented in appendix B. These deliveries consist of all the different types of products, most are stored in the warehouse and a small part is transported to the staging lanes to be cross-docked.

The receiving of each type of product is using a different procedure, but all procedures start the same. As the truck arrives, a separation is made between trucks from Nijman/Zeetank or from other suppliers. When a Nijman/Zeetank truck arrives it will enter the unloading bay and will immediately start unloading, but when a truck from another supplier arrives, they will be assigned an unloading time. Each truck carries a delivery note which lists all SKUs it delivers. When forklift operators store the SKUs in the appropriate zone, they manually add the storage location to the delivery note. These are then added in the ERP by the operators of NSG Pilkington. The raw material will receive a container label from NSG Pilkington after it has been stored, so it is possible to track the movements of the container through the production.

For the WIP, the procedure continues by checking who made the delivery. When done by Nijman/Zeetank, a forklift operator confirms the location the container was stored in by scanning the container label. When delivered by another supplier, an employee of NSG Pilkington will confirm the location in the ERP.

The second and third inbound flow of products are the WIP products coming from the first part of production and the finished products coming from the second part of the production that will be stored pending further processing or shipment (figure 2.4). These products will be placed in the transfer zones located just outside of the warehouse doors, from which an operator of Nijman/Zeetank will pick it up. He will then transport the container to a storage zone assigned to this type of container and add the location in the ERP by scanning the container and location label.

2.4.2 Store

Currently, when storing a container, the operator decides where he is placing it. The operator is limited in his choices for the selection of a storage bin as the warehouse is divided in zones that are designated to certain types of product (table 2.1). A number of these zones is further divided in areas set specifically for certain customers to maintain an overview of the warehouse. When a container is stored, the operator uses a barcode scanner to add the location of the container into the ERP system of NSG Pilkington. If this container was picked from the unloading dock, its location is added manually to the delivery note and later entered in the ERP.

At the moment the warehouse uses a pallet block-stacking pattern for all zones (Gu, Goetschalckx, & McGinnis, 2010). The pallets are positioned on the floor and subsequent pallets are stacked on top or positioned in front. To keep track of the current stock levels and container locations, weekly inventory scans are conducted where every container in the warehouse must have its barcode scanned and have its location added. This action is executed for an average number of 33.000 times every month, with a standard deviation of 8.600 scans per month (table 2.2). Most of these scans can be attributed to zones S and C as these on average make up 65% of all scan moves.

At the moment, the SKUs are placed in storage locations based upon the layout of the warehouse and the individual decisions of the forklift operators. This leads to a number of unnecessary movements in the picking process to access the required SKUs. When the blocking SKUs are moved in order for the required container to be picked, they can either be moved back or be left in another storage location, according the preference of the operator. When the SKUs are left in another storage location, the operator has to scan them to change their location in the ERP system. The number of registered unnecessary movements per zone per day can be found in table 2.3.

Month	A	C	P	S	Staging	**Total**
January	9.703	16.041	3.959	14.945	1.662	**46.310**
February	10.016	11.985	2.454	13.151	2.344	**39.950**
March	6.770	9.543	2.356	10.004	1.432	**30.105**
April	5.691	9.066	1.587	8.119	5.789	**30.252**
May	10.694	15.098	2.907	12.906	12.172	**53.777**
June	5.753	7.497	1.490	7.268	1.263	**23.271**
July	5.968	8.065	1.429	11.137	1.221	**27.820**
August	7.385	11.575	1.827	13.570	743	**35.100**
September	4.858	7.647	1.456	11.440	1.286	**26.687**
October	6.080	9.000	1.537	10.633	1.253	**28.503**
November	6.624	12.958	2.653	10.228	1.374	**33.837**
December	6.153	10.024	1.380	8.221	822	**26.600**
Average	7.141	10.708	2.086	10.968	2.613	**33.518**
Standard deviation	1.840	2.727	764	2.279	3.155	**8.648**

Table 2.2. Inventory scans over the year 2015

Area	Average	Standard deviation
A	93	151
C	121	182
P	30	61
S	148	280
Staging	10	18
Total	**401**	**372**

Table 2.3. Unnecessary movements per day over the year 2015

2.4.3 Retrieve

The warehouse has three different flows that move product out of the warehouse, as described in figure 2.2. The first is the raw material moving to the first part of the production, the second is the WIP that moves to the second part of the production or that is being shipped, and the last are the finished goods that are being shipped.

When the first part of the production line needs raw material, NSG Pilkington prints an order form and hands that to the foreman of the warehouse, and a request e-mail is send as well. The production line makes a request for a type of product in the warehouse and it is required by NSG Pilkington that Nijman/Zeetank picks the SKUs according to the First-In, First-Out (FIFO) rules. An operator checks the inventory and marks the required container that has been residing in the warehouse the longest. The operator searches for the container in the warehouse and retrieves it from its storage location. As raw glass is delivered in either metal or wooden containers and the production line is only capable of processing metal SKUs, the glass might need repackaging. When the glass has been delivered, the operator adds the storage location from where the glass came to the order form and an operator of the production line signs off for the delivery. The forklift operator then returns the order form to his foreman. These order forms are collected and at the end of the shift returned to NSG Pilkington. Both NSG Pilkington and the production line then confirm the delivery in the ERP.

The procedure for delivering WIP to the second part of the production starts in the same way as for the raw material. A forklift operator is send to find and pick the container, he adds the location to the order form and delivers the container to the transfer zone. Here the production line operator signs off on the delivery after which the forklift operator returns the order form to the foreman. He collects the forms and hands them back to NSG Pilkington at the end of the shift to be entered in the ERP.

The final outbound flow are the products that are picked and moved to the staging areas, awaiting shipment. This process starts with a monthly schedule that contains all times, dates and shipment numbers. Before the trucks arrive to be loaded an e-mail is send to the foreman containing the details of the shipment which can also be found in the ERP system. For the shipments the individual SKUs are requested from the warehouse, not the type of product in the SKU. The foreman checks the inventory and marks the SKUs that are to be shipped. He then adds the shipment details on an information board, beginning with the number of SKUs, the destination and the departure date and time. Figure 2.5 shows an example of such information. From here a forklift operator collects the picklist from the foreman and moves into the warehouse. He uses the picklist to move to different storage locations that contain SKUs that need to be shipped. At a storage location the operator manually searches for the correct container by comparing the container label to the ID number on the picklist. When the correct container is found, the operator marks it with a flag and moves on to find the next. When all SKUs on the list are found he marks that on the information board with the green ‘flag’ as seen in figure 2.5. This informs other operators that they can start picking this order. They move into the warehouse en visually search for the flags that mark the SKUs and proceed to remove the SKUs blocking the path and position these either in the aisle or in another storage location. When the path to the marked container has been cleared, the operator moves it to the aisle and either returns the other SKUs or clears a path for the next one. After the operator has accumulated a number of SKUs in the aisle a larger forklift collects and moves them to the staging area.

Figure 2.5. The information board with shipment details

2.4.4 Accumulation and Sorting

This process takes place at the staging area as this is were all SKUs are accumulated for the different shipments. When all SKUs with the right colour flag are picked and moved to the staging area, the foreman checks if the shipment is complete. If a container is missing he tries to find the reason for its absence and adds it to the information board. In 2015 less than 1% of all shipments was delayed due to missing SKUs in the responsibility of Nijman/Zeetank. Most delays were caused by trucks arriving late, accounting for 41.6% of all shipments. Further delays were caused by SKUs still being in production (5.7%) and SKUs that were repackaged (4.6%).

When the shipment is complete NSG Pilkington prints the labels that are requested by the customer and delivers these to Nijman/Zeetank. These are attached to the SKUs and a picture is taken as proof that the labels are attached correctly. When the truck arrives in the loading dock, a large forklift loads the SKUs and the shipment leaves the production plant.

2.5 Product flows

Using the movement data of the year 2015 gained from the ERP system of NSG Pilkington, the daily product flows were found and presented in table 2.4. These flows represent all movements made by SKUs from one origin to one destination, with a average of 1.455 movements per day. The table does not include the movements made to reach a container that is to be picked, as described in section 2.4.3. Figure 2.6 shows the layout of the warehouse and the different zones. The areas that are not assigned to different zones are used by NSG Pilkington

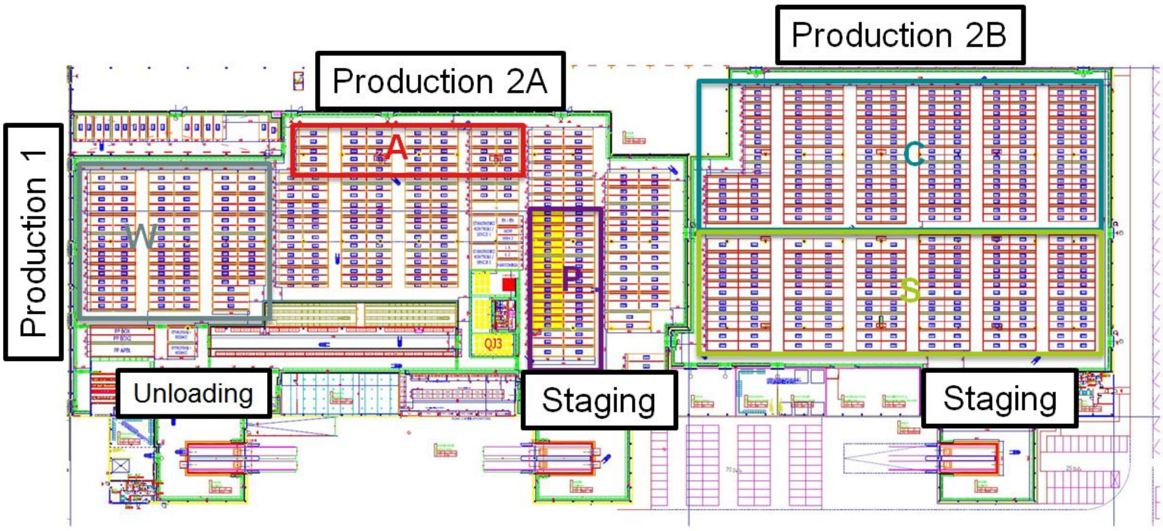

Figure 2.6. The different zones in the warehouse

for quality control, storage of production tools, or the storage of other components used in the production.

Table 2.4 shows that Production 1 splits its incoming SKUs as it only receives an average of 45 SKUs per day, whereas it returns 107 SKUs per day. This is caused by the fact that the raw glass enters the warehouse as a flat sheet of glass and leaves the production line as a curved windshield. The SKUs with the flat sheets of glass can carry a far larger number of sheets than the SKUs with windshield. Production 2A also splits its incoming SKUs, as it only receives 76 SKUs on average and sends back 145 SKUs. This is likely caused by the fact that it produces both finished products and WIP. Another location that splits SKU is the repackaging in zone P, which receives 4 SKU per day, and returns 33. Production 2B does not split its SKUs as it receives an average of 114 SKUs and returns 97 SKUs, it is more likely that SKUs are combined in this part of the production. All flows combined, the warehouse in Chmielów moves an average of 1.455 SKUs per day.

From the ERP data received from Nijman/Zeetank it is derived that the average shelflife of any SKU is around 10,6 days with a standard deviation of 29,4 days.

2.6 Forklift

The forklifts of Nijman/Zeetank are used to move product to fulfil customer orders. This, however, is not the only thing the forklift and its operator do in the warehouse. They search

Origin \ Destination	A	C	P	S	W	Prod. 1	Prod. 2A	Prod. 2B	Staging
Unloading dock	107±58	96±48	4±8	106±68	65±68				
A							76±56		135±69
C								114±68	161±68
P									33±30
S									164±68
W						45±21			
Production 1	58±32	26±21		23±15					
Production 2A	44±36	80±46		21±21					
Production 2B	11±16	62±36		24±23					

Table 2.4. Product flows per day over the year 2015

for SKUs and mark them with flags for shipments, when marked they search for the flags by moving around the warehouse. When they locate the flags they start digging them out and while one forklift is digging, another will have to reroute as the aisle is blocked by other SKUs. These different activities of the forklifts are described below, after which a distribution is made in terms of time per SKU.

2.6.1 Fleet mix

The operation in the warehouse is currently executed by the fleet of forklifts as shown in table 2.5. Forklift 25 and 26 are used to bring gathered SKUs from the storage area to the staging lanes, all other forklifts are used to store and pick all other SKUs.

ID	Capacity [ton]	Year of Production
9	3,5	2013
10	3,5	2013
11	3,5	2013
12	3,5	2013
13	3,5	2013
14	2	2012
20	2	2013
25	7	2013
26	7	2013
30	1,6	2013
37	2	2013
38	3,5	2014
39	3,5	2014
43	3,5	2015

Table 2.5. Current fleet mix

2.6.2 SKU movement

This activity contains all the movements required to store and retrieve a single SKU, starting with picking it when it arrives at the warehouse, transporting and putting the SKU in its storage location, from where the SKU will be picked and transported to its destination. This is a necessary movement that can not be eliminated from the process.

2.6.3 Dead-heading

When a retrieval order arrives at the warehouse it is passed on to a forklift operator, who then moves his forklift into the storage area and searches for the SKU that is requested. At this moment the forklift is moving without product, which is called dead-heading (section 3.1.2). As the time that this activity consumes is not used productively, an attempt should be made to minimize this.

2.6.4 Digging

After the requested SKU is located, the forklift must retrieve it from the storage area. At this point this activity requires a large amount of time as the forklift operator has to remove all product blocking his way. This product is then moved to another storage area, or placed in the aisle, until the operator has access to the ordered SKU. The operator then places the product in the aisle and either continues to dig to retrieve more product, returns the blocking SKUs, or changes the locating of the blocking SKUs in the ERP.

2.6.5 Waiting/Rerouting

A direct effect of the digging is that different aisles will be blocked. This then leads to the fact that other forklifts will be forced to change their routes and potentially increase the distance they need to move, or even have to wait until they can reach another storage lane, adding time to finish the task at hand. As this is caused by the digging, it is necessary to try and reduce the amount of extra moves that need to be made.

2.6.6 Flagging

The flagging is only done on shipments as these consist of orders filled with a specific item list. A forklift operator is handed a list of SKUs that need to be picked, and he starts looking for them. While he is looking for the SKUs on the list, his forklift is not moving, which is a waste of resources that need to be reduced, or even eliminated.

Activity	Time [min]
SKU movement	2,76
Dead-heading	2,12
Digging and Waiting	(estimate) 3,22
Flagging	0,82
$\textbf{Total}_{\textbf{shipment}}$	**8.92**
$\textbf{Total}_{\textbf{production}}$	**8.10**

Table 2.6. Results of the measurements and estimates of the forklift times

2.6.7 Distribution

A distribution between these activities is made by measuring the times needed to perform them multiple times and determining the average time. As 'Flagging' is only done for shipments, two separate sets are made, one for the shipments in figure 2.7 and one for the production lines in figure 2.8.

Measurements were done to determine the amount of time necessary to pick a single SKU, however some values were found to be too diverse to reach a conclusion about, and are therefore estimated based on the information concerning the SKU movements. These values are those of the waiting and rerouting, and those of the digging. The waiting and rerouting is estimated because the movements of the forklifts through the warehouse are not recorded and therefore no statement can be made. The digging is estimated because in the current process, the operators can see if more than one required SKU is in a storage bin and can use this information to dig out more than one SKU at a time. Therefore it was not possible to obtain a clear value for the digging.

To make the estimates, the total operational time of all forklifts was divided by the number of SKUs moving through the warehouse on a peak day, resulting in a minimum average working time per SKU. From this value the SKU movement time and the Dead-heading time were subtracted, resulting in an estimate for the time required to dig and the time spend rerouting and waiting combined. All results of the measurements and the estimated values can be found in table 2.6. For figures 2.7 and 2.8 it was assumed that the digging takes up more time than the waiting and rerouting and is therefore shown as 90% of the estimated value.

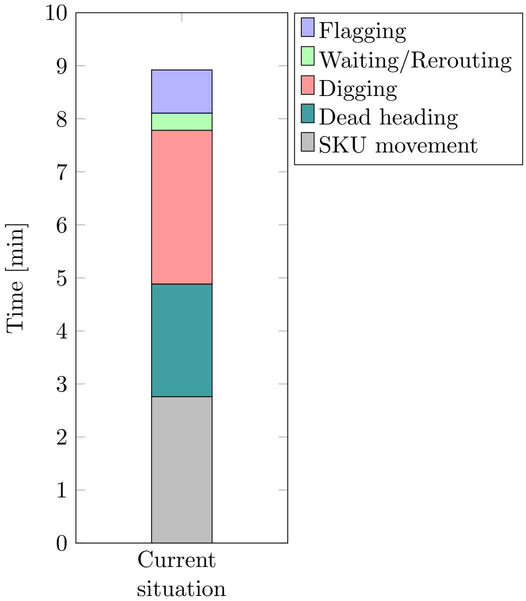

Figure 2.7. The time spend by a forklift collecting a SKU for a shipment

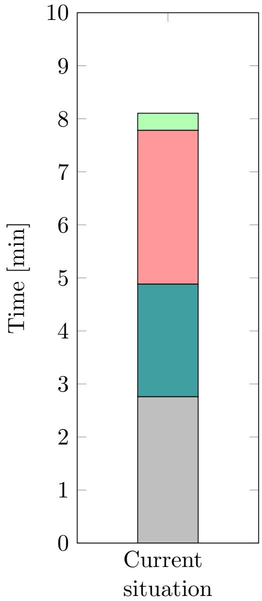

Figure 2.8. The time spend by a forklift collecting a SKU for the production line

2.7 Problems/Conclusion

When looking at the different parts of the warehouse operation, it is found that each has the potential for improvement. For the receiving part the problem is that each type of product has a different procedure and even a different procedure if it arrives from the unloading dock or from the production line. This is a way of operating that creates confusion among the operators and can possibly lead to mistakes.

In the storage process it was found that the storage location assigned to a container is chosen by a forklift operator, within a certain zone. In his decision making he does not take into account any information about the container other than in which zone it must be placed based on the type of product. Information on when it will leave the warehouse is left out of consideration. Another problem in the storage area is the combination of the layout and the set rules. For the raw and the WIP glass, the storage areas are designed as a block stack, and the product is retrieved using the FIFO rule, which leads to a large amount of excess product handling as each SKU can be anywhere in a storage lane.

When a shipment order has been sent to Nijman/Zeetank, all SKUs that are requested will be accumulated on a staging lane near the shipment docks. Here the foreman checks if all SKUs are present, if not he tries to find out where it is and why it is not in the staging area.

All of these problems have one thing in common, namely the lack of information available during the different actions. The different procedures for the receiving are all caused by the way information is handled during that phase, the difficulties in the order picking are caused by the storage location assignment, in which no clear directions are given, and finally, in the staging area, no information about missing SKUs is available.

Nijman/Zeetank looks to improve their operations to be able to keep up with the growing production of NSG Pilkington, which is the largest incentive to improve the operations.

Chapter 3

Analysis

A warehouse is a facility in the supply chain that brings products together to reduce transportation cost, achieve economies of scale in manufacturing or in purchasing or provide value-added processes and shorten response time (Subramanya, Rangaswamy, et al., 2012). All supply chains have warehouses in one form or the other, in general they are classified into production warehouses and distribution centres and by their roles in the supply chain they can be classified as raw materials warehouses, work-in-process warehouses, finished good warehouses, distribution warehouses, fulfilment warehouses, local warehouses direct to customer demand, and value-added service warehouses (Subramanya et al., 2012). A warehouse requires labour, capital in the form of land, storage-and-handling equipment and information systems, all of which are expensive (Bartholdi III & Hackman, 2011). Even though warehouses mean a sizeable investment, they provide useful services that are required to improve the performance of the operation. This chapter will answer the following research questions:

2. What is warehousing?

3. How can the operational performance be measured?

3.1 Generalisation

This section describes a general unit-load warehouse by separating the different types of flows using the PROPER model of Veeke, Ottjes, and Lodewijks (2008). It will describe the different steps in each process and the different performance indicators, from which section 3.1.2 will define the perfomance indicators.

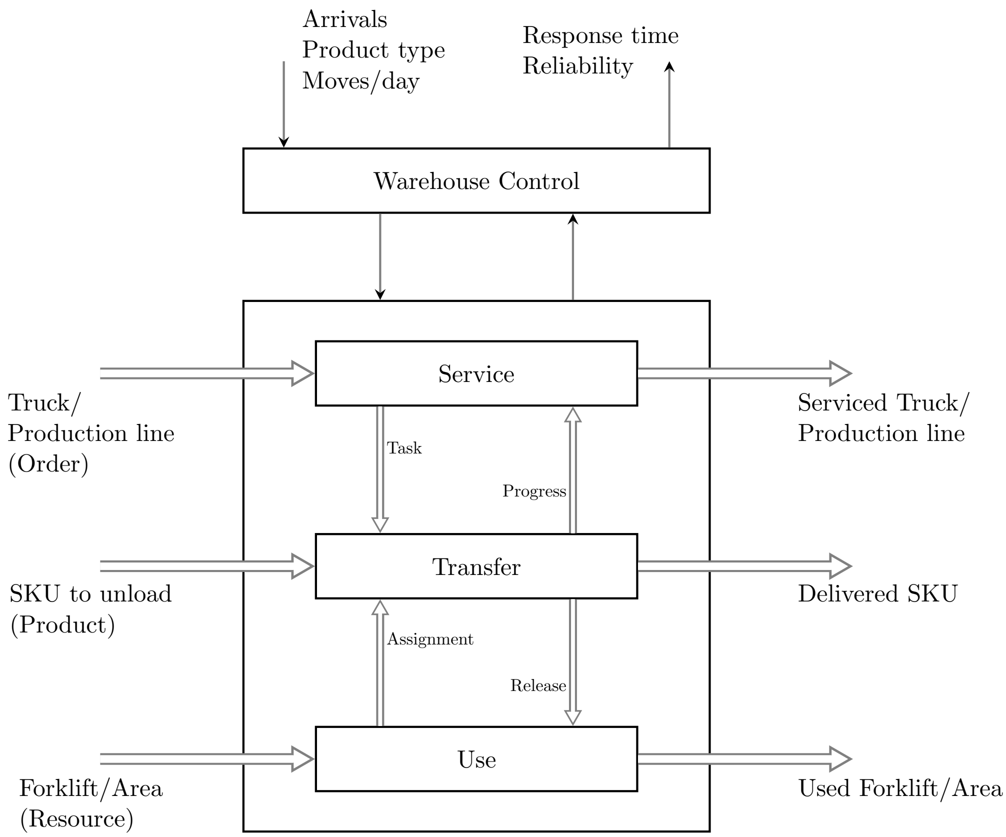

Figure 3.1. The PROPER model for the warehouse

3.1.1 Unit-load warehousing

A warehouse handles product moving through that is delivered to it, either from trucks or a production line. This can be classified as two different types of delivery, a batch type (the trucks) and a continuous type (the production line). This product is then stored awaiting orders to be fulfilled, which can also be divided in the two types, batch and continuous.

The Warehouse Control shown in figure 3.1 is the connection between the warehouse and its environment, reporting the performance to the management and perhaps to contractual partners. The performance is positioned at the top between the arrows together with the requirements, as the performance is reported in the same terms as the requirements.

When moving into the system, the requirements should be translated to the requirements for each separate flow, from which there are five in the PROPER model:

1. The trucks and the production lines are the *order flow* as these are the entities that request SKUs to be transported to them. The order process is defined as 'Service' as it is mainly concerned with the service the system provides to its customers.

2. The SKUs are the *product flow* in the system. This process is defined as 'Transfer' as its main objective is to move the product through the warehouse, and is not directly related to the service provided by the warehouse.

3. As the warehouse only uses forklifts to move SKU through the warehouse, they make up the *resource flow* together with the actual warehouse space.

4. The *task flow* runs between the Service and the Transfer function, or the order and product flows. A task is defined as a single order to store or retrieve an SKU and therefore a completed SKU transfer consists of two tasks, one to store and one to retrieve, with the storage area in between. The Transfer function returns the progress of the tasks to the Service function.

5. The *assignment flow* between the Transfer and the Use function assigns resources to the tasks, so a forklift will be assigned to pick up a SKU and a storage location will be assigned where the forklift will store it. After storing the product, the Transfer function will release the forklift, therefore making it available for another task.

The task and assignment flows create insight in the factors that influence an operations performance. To be able to find the different performance indicators, the following sections will zoom into another level of the model and separate the different horizontal flows, creating different models for each flow.

Orders

As mentioned before, a warehouse handles product either in batches from trucks or continuously from production lines. This leads to a separation in flows to a 'Truck'-side and a 'Production line'-side as shown in figure 3.2. Each truck consists of a batch of orders as they transport multiple SKUs, both incoming and outgoing, whereas the production lines form a continuous flow of orders as they continuously produce products, constantly requesting input materials and returning output materials. This leads to the division of tasks in those for the production lines and those for the docking bays, and tasks for storage and retrieval.

By measuring the number of performed tasks per hour, the Control Service function is able to judge the progress of the service. Furthermore the task lead times and the number of tasks released are measured to gain an indication of the service provided by the warehouse.

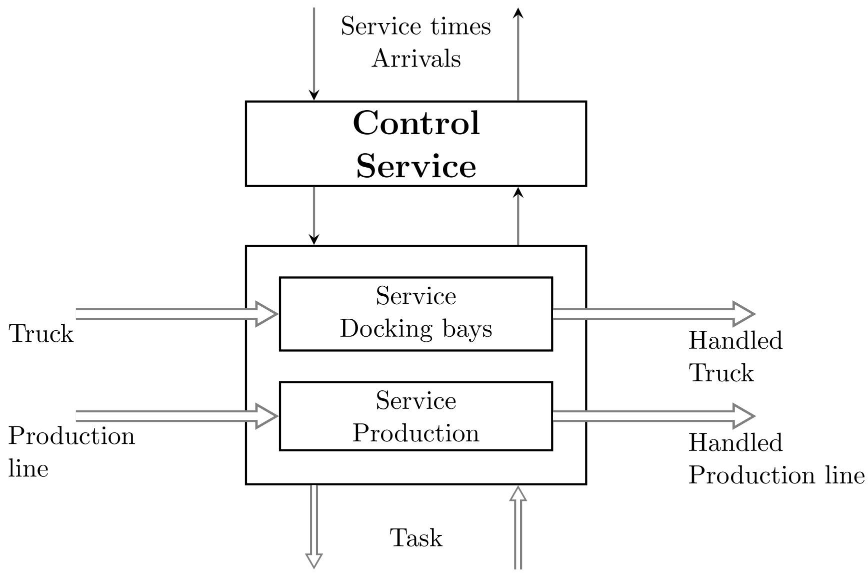

Figure 3.2. The order flow at the warehouse

Products

The separation of the flows -as described in section 3.1.1- is found to have an overlap in the storage area. The products arrive at the different locations either by truck or by being placed in a transfer zone just outside the warehouse coming from the production lines. From here the SKUs are unloaded by a forklift that moves them into the warehouse and stores them at a given location. When a retrieval task is given, a forklift will retrieve the SKU from the storage area, transports it to the loading area and loads it in a truck or into a transfer zone near the destination production line.

The equipment used for each function is shown in the bottom right corner of the function blocks as shown in figure 3.3. As all product is moved by forklifts, this is set in every function. The Control Transfer function combines the released tasks from the order flow with the assigned resources to perform the transfer function. Because the process can be divided in two separate parts that are executed by a single forklift, the tasks are split in a pick up task and a deliver task, with the transport as a part of the deliver task. When a task is handled it is returned to the Service function and the used resources are released to the Use function described in section 3.1.1.

As the forklifts are used for all operations within the warehouse, the division of tasks is key to a smooth operation. The available time per resource must be divided over the docking bays and the production lines, as well as over the storage and retrieval tasks. This could be a disadvantage as certain tasks can be left to long, causing delays, but it can also be an

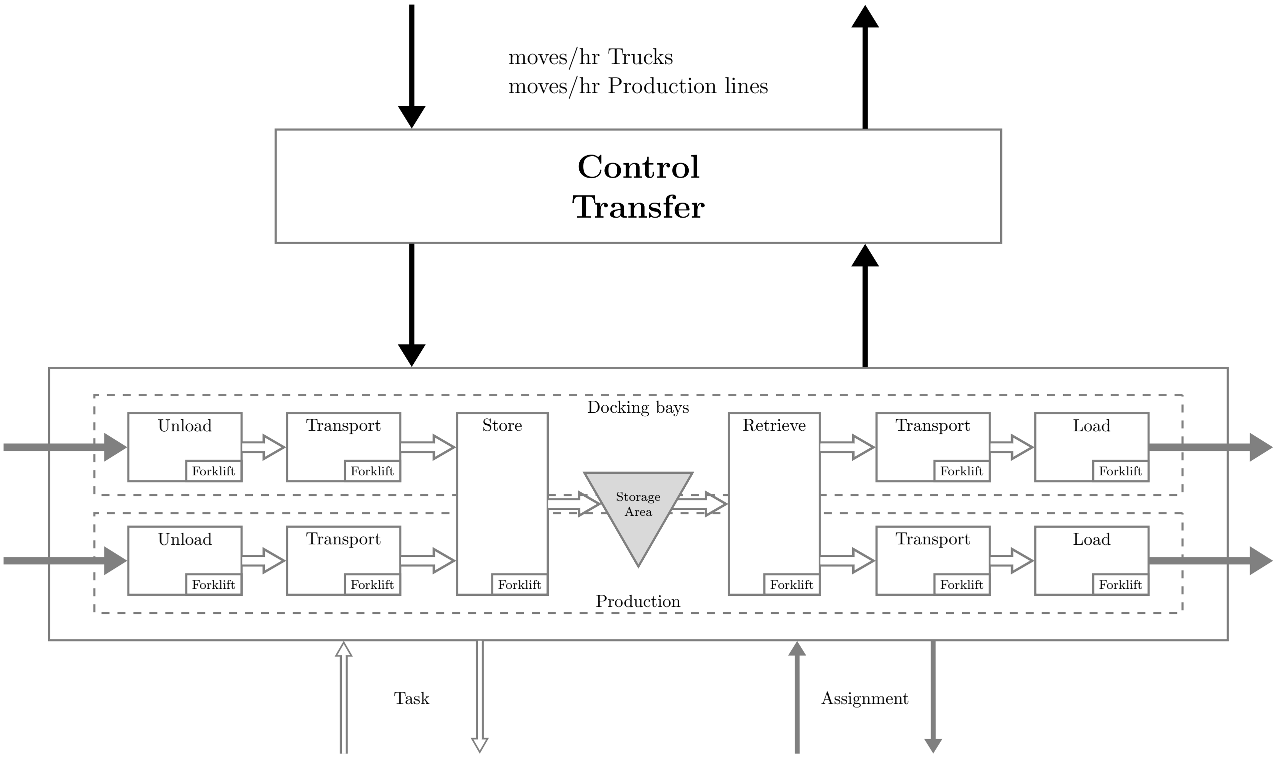

Figure 3.3. The product flow at the warehouse

advantage, as it is possible to reduce the time a forklift moves through the warehouse without moving a SKU (Dead-heading).

When storing a product, the Control function has to consider the different areas of the warehouse, as zones can be designated to certain products and have different rules apply to them following the type of product stored there. The Control Transfer function measures the amount of moves per hour to make sure the intended results are met. To prevent the creation of bottlenecks, it is key that all functions in figure 3.3 have the same goal in terms of amount of moves per hour. The operations performed at each function block are:

Unload Upon arrival the product is unloaded and either stored immediately or staged to be put away. It is likely to be scanned to register its arrival so ownership is assumed, payments dispatched, and so that it is known to be available to fulfil customer demand (Bartholdi III & Hackman, 2011). Usually products arrive in large units, such as pallets, which can be stored as a whole.

Store Before a product can be placed in storage, a location must be determined. This location determines to a large degree how quickly and at what cost you can later retrieve it for a customer. To achieve this, a second inventory must be kept which contains information about the storage locations, such as the availability, the size of the location and the amount of weight that can be handled etc.. To determine where a product is being stored, several different policies can be chosen based on the amount of information available, which will lead to a certain Storage Location Assignment Problem (SLAP). The process will be described in more detail in section 3.3.1.

As product is stored in its designated location, the location should be recorded as this information will subsequently be used to guide the order pickers in retrieving the product for customers.

Retrieve When the warehouse receives a customer order it must first verify in the ERP system of NSG Pilkington that the inventory is available to ship, then the picklists must be produced to guide the order picking and then the picking and shipping must be scheduled. Order picking generally accounts for 55% of all warehouse operating costs (Bartholdi III & Hackman, 2011) and may be further broken down as in table 3.1.

Activity	% Order-picking time
Travelling	55%
Searching	15%
Extracting	10%
Paperwork and other activities	20%

Table 3.1. Breakdown of the order-picking operation (Bartholdi III & Hackman, 2011)

Table 3.1 shows that 55% of the order picking operation consists of the travelling of the pickers. Therefore a considerable part of the design of the order picking process is directed to reduce this unproductive time (Bartholdi III & Hackman, 2011).

Each customer order consists of a number of order lines, which each contain a product type and the number of parts that are ordered. First the inventory is checked to see if there is enough product to complete the order, if there is a shortage, an order is made to restock the inventory. When the order can be completed, the order lines may be sorted to match the layout and operations of the warehouse to increase the efficiency.

A pick line is an instruction to the order pickers that tells them where to go and what to pick in what quantity and units of measure. As each pick line represents a location to be visited, and since travel is the largest labour cost in a typical warehouse, the number of pick-lines is an indication of the labour required. To reduce the travel times between picks, a Warehouse Management System can create picklists that have the pick lines in a sequence in which the picker will encounter the items when moving through the warehouse. The picklist is either a physical sheet of paper, a sequence of requests communicated by a stream of printed shipping labels, by light, Radio Frequency (RF), or voice transmission.

Load In shipping, completed customer orders are loaded in freight carriers, while trying to completely fill these by staging completed orders to accumulate as much cargo for one destination. Another reason to stage freight is the possibility of reverse order of delivery, so the first pallet or case in is the last to be delivered. As the freight carrier is filled it can be scanned to register its departure from the warehouse and an inventory update may be sent to the customer.

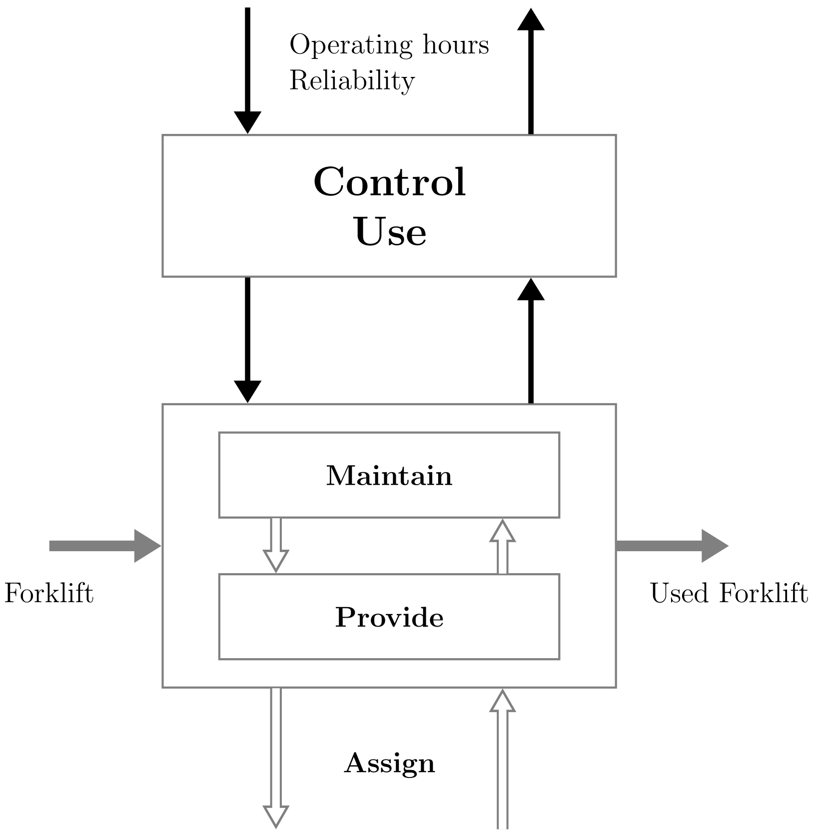

Figure 3.4. The resource flow at the warehouse

Resources

The aim of the Use function is to provide sufficient resources for the operation in the Transfer function. As the storage area is an unmanned and non-moving resource, it is always available and has a certain capacity. The forklifts however, are manned resources and as they move around, they have a chance to breakdown and require regular maintenance. The forklifts therefore cycle between being in maintenance and being available for tasks as is visible in figure 3.4. The Control Use function measures the utilisation of the resources and their effectiveness. For a forklift this means that not only the amount of time it is working is measured, but also the number of unnecessary movements, which is an indicator of the effectiveness.

When a storage location is only partially filled with material, it is called honeycombing, which may occur both horizontally and vertically (Tompkins & Smith, 1998). Figure 3.5 shows examples of both types of honeycombing, with (a) and (b) showing a plan view and (c) and (d) showing an elevation view. Where honeycombing is an effect of the underutilisation of the storage area. The effect when a storage area holds to much product is that some products will get blocked, resulting in the double handling of product, an unnecessary movement.

3.1.2 Performance indicators

The previous sections lead to the following performance indicators:

- Orders
  - Performed tasks per hour
  - Task lead time
  - Released tasks
- Products
  - Moves per hour
- Resources
  - Forklift utilisation
  - Storage area utilisation
  - Unnecessary movements

These performance indicators are all concerned with either the effectiveness, the efficiency or the throughput of the system. Using these indicators, different policies and decisions can be compared and a fitting solution can be found.

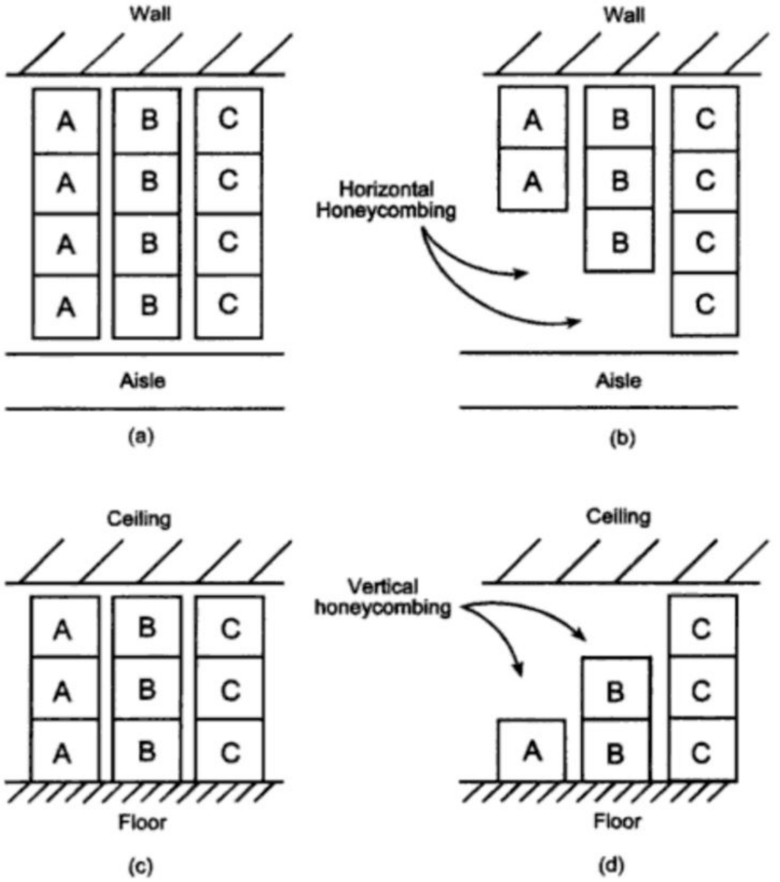

Figure 3.5. Horizontal and vertical honeycombing. (a) Plan view of bulk storage area-no honeycombing. (b) Plan view of bulk storage area showing horizontal honeycombing. (c) Elevation view of bulk storage area-no honeycombing. (d) Elevation view of bulk storage area showing vertical honeycombing (Tompkins & Smith, 1998).

Performed tasks per hour

The number of performed tasks per hour are measured, to allow the Control Service function to judge the progress of the service. Using the supply and demand for the truck and production line a goal can be set so the Control Service function can compare the performance with it. In reality this is measured by dividing the amount of tasks completed by the time over which there is measured, or:

$$\dot{n}_{performed} = \frac{n_{performed}}{T_{elapsed}} \tag{3.1}$$

with $\dot{n}_{performed}$ the number of performed tasks per hour, $n_{performed}$ the performed tasks, and $T_{elapsed}$ the time elapsed in hours.

Task lead time

The task lead time is the time from the moment the store or retrieve task is released into the system, until it is completed. This time can be used by the Control Service function to gain insight in the level of service that is being given to the customer and the flexibility of the operation. The lower the lead time, the more flexible the system is, as it is able to react quickly to the different demands.

Released tasks

By measuring the amount of released tasks into the system, the Control Service function can determine the demand for service. Using this information it may try to find trends and peaks and inform the Warehouse Control, which in turn can use this information to try and modify the capacity accordingly.

Moves per hour

Using the supply and demand of the trucks and the production lines a goal can be set for the amount of moves that need to be made by the system. Measuring these moves can show a lack of resources when the goal is not met, or when the number of moves exceeds the goal it can indicate that SKUs are double handled and adjustments need to be made in certain decisions.

Forklift utilisation

As the forklifts are the only resource with operational costs and have a initial investment, they carry a large amount of the day-to-day expenditures of a warehouse. Therefore it is key to increase the efficiency of the forklifts, which can be achieved by reducing the time dead-heading, which is not part of a storage or retrieval task. This time can be separated in three parts, idle time, dead-heading, and unnecessary movements. As idle time and dead-heading are both measured in moments of time, they are combined in the utilisation, and the unnecessary movements are lines in the ERP system, they are separated and described in further detail below.

The idle time is the time a forklift is not moving toward or with a SKU, so it is either standing still or moving toward a location where it can safely park and wait for another task. This does not include the time that is required to move to the battery changing area and change its battery, as this time is essential in the operation of the forklift.

$$T_{idle,i} = T_{op,i} - T_{work,i} \tag{3.2}$$

Equation 3.2 shows how the idle time of forklift i, $T_{idle,i}$, is the result of the subtraction of the working time of forklift i, $T_{work,i}$, from the total operational time of forklift i, $T_{op,i}$. As the changing of the battery is essential in the operation, the time required to do so is included in $T_{work,i}$.

Movements in a unit load warehouse are mostly to store or to retrieve pallets, which means that a forklift is moving empty at least half of the time, called *single-cycle*. When a forklift has a task to store and to retrieve a SKU, it is called *dual-cycle*.

Storage area utilisation

As the storage area is a large static resource with a considerable initial investment, its utilisation is a key indicator of the assignment of products. A large factor in the under utilisation of the storage area is honeycombing, as explained in section 3.1.1.

Unnecessary movements

When a SKU is ordered to be retrieved from the storage area, a forklift is assigned to that retrieval task. When another container blocks the ordered SKU, the forklift has to move this container, which counts as a unnecessary movement. These movements influence other performance indicators, as the moved containers are placed in other storage areas, limiting the storage utilisation, or placed in the aisles, blocking them for other forklifts, increasing the distance they have to move.

3.2 Decision making

Decisions are made on all levels of an operation, from the managers on the top, who decide what the company should aim for in the future, to the operators on the floor, who decide on how to execute the next step of the operation on the job at hand. Or if translated to a warehouse, where to store a SKU. These decisions can be categorized in three different levels, Strategic, Tactical and Operational. This section will describe those levels and what decisions are to be made on those levels in a warehouse to answer the following research question:

4. What are the decisions made on the different levels (Strategic, Tactical, Operational)?

3.2.1 Strategic

The decisions made on the strategic level are mostly made by high level managers and are based on the current operation and its performance, on what the decision makers want the operation to be, and how to get to there. The decisions on this level are major choices of actions and influence large parts of the operation, contributing directly to the common goals of the enterprise and lean on the structural change in the operation. To begin this decision making process, the current operation should be assessed, making it possible to set goals for the future. This assessment involves a situation analysis, self-evaluation and competitor analysis, both inside the enterprise as well as outside. By using the results of the assessment, objectives can be set for the operation. These objectives involve creating long term projections for the future, mission statements, overall corporate objectives, strategic business unit objectives, and tactical objectives (Boundless, 2015).

In the case of Nijman/Zeetank, their strategy is to increase the efficiency and the quality of the service provided in their warehouse, as described in chapter 2. On the strategic level the decisions will answer the question *'What resources can I use?'*, as this is a long term decision and will decide if they continue to work with the current equipment or change the number of resources in the warehouse.

3.2.2 Tactical

Tactical decisions are made by all levels of management in an operation and involve changes in the processes of the operation. Here the existing process and its management is reviewed and changed to eliminate nonvalue-adding procedures and to balance the different flows.

The tactical decision making focuses on balancing the process capacity with the market demand, emphasising the flexibility of resources and processes. By using creative solutions it is possible to shift the flow or the capacity of the existing systems with minimal capital investment (McNair, Vangermeersch, et al., 1998). These solutions are directed to achieve the vision and objectives set by the decisions made on the strategic level. Because the tactical decisions concern themselves with a more specific problem, their effects are on a intermediate term, and when requirements are not met, they can be adjusted more easily than a company strategy.

On the tactical level the decisions will answer the question *'How do I use my resources?'*, as this will influence the day-to-day operations of the warehouse, and will create guidelines in how to handle the different parts of the process. A typical tactical decision is the choice of Storage Location assignment policy, which is described in more detail in section 3.3.

3.2.3 Operational

The operational decisions are made for the short term and are aimed at their impact on current profits and costs. Due to their short term horizon and focus on the day-to-day operations, these decisions are often taken repetitively. The idea behind these decisions should be to streamline the process, to minimize the cost and work as quickly and efficiently as possible. As these decisions are based on facts regarding the current events, they do not require much business judgement.

It is key that the manager is sufficiently informed and therefore, the information system should be able to produce real-time information on the subject at hand. These decisions should be combined with operational objectives that, if met, will lead to the achievement of tactical objectives (Gunasekaran, Patel, & McGaughey, 2004). Furthermore, the decisions made should be able to answer the question *'What do I do when... happens?'*

In a warehouse, the operational decisions concern the day-to-day operations and involve the resource utilisation, the quality of the service provided, the timely delivery of SKUs to the different output zones and the different disturbances in the process.

3.2.4 Conclusion

As the warehouse is already in operation, the amount and kind of resources are already chosen, both decisions on the strategic level. To improve the efficiency and level of service to the customer, it is key to make the right decisions on the tactical level. These decisions include the allocation of storage space to products (section 3.3) and the division of the forklifts across the different tasks in the warehouse. Therefore, the decision support system that is to be designed should consider the different tactical policies and show their effects on the operational performance.

3.3 Storage Location Assignment

3.3.1 Storage Location Assignment Problem

The Storage Location Assignment Problem (SLAP) is to assign incoming products to storage locations in the warehouse in such a manner that the material handling cost are reduced and the space utilisation is improved. The SLAP is defined by Gu, Goetschalckx, and McGinnis (2007) as follows:

Given:

1. Information on the storage area, including its physical configuration and storage layout.
2. Information on the storage locations, including their availability, physical dimensions and location.
3. Information on the set of items to be stored, including their physical dimensions, demand, quantity, arrival and departure times.

Determine:

1. The physical location where arriving items will be stored.

Subject to performance criteria and constraints such as:

1. Storage capacity and efficiency.
2. Picker capacity and efficiency based on the picker cycle time.
3. Response time.
4. Compatibility between products and storage locations and the compatibility between the products.
5. Item retrieval policy such as First-In, First-Out (FIFO), Last-In, First-Out (LIFO), Batch First-In, First-Out (BFIFO). When using the BFIFO policy, items that arrived in the same replenishment batch are considered to be equivalent.

The information about the storage area is almost always available in a warehouse and in all automated and some mechanised warehouses the availability is also known. Depending on the available amount of information on the arrival and departure of products stored, the SLAP can be divided in three classes:(1) item information, (2) product information, (3) no information.

Item Information

The storage location assignment problem based on item information (SLAP/II) assumes that complete information is known about the arrival and departure time of the individual items. According to Gu et al. (2007) & Goetschalckx (1998) this leads to a specially structured assignment problem known as the Vector Assignment Problem (VAP). This VAP has the special property that two items can occupy the same storage location, provided that they do not occupy it at the same time. The name comes from the fact that the occupation is no longer expressed as a single binary status variable, but as a vector over the different time periods. An example of a heuristic SLAP/II policy is the Duration of Stay (DOS) policy of Goetschalckx and Ratliff (1990). This policy determines the storage location based on the individual duration of stay of the products, and products with the shortest DOS are assigned closest to the Input/Output (I/O) point.

Product Information

The storage location assignment problem based on product information (SLAP/PI) uses the information about the product, and items are instances of the product. The products may be classified into product classes based on size and usage rate. Individual items are assigned to product classes based on their characteristics, and products are assigned to different storage locations.

Some examples of policies based on product information are Dedicated Storage (DED), Random Storage (RAN) and Class-Based storage. Each of these policies is derived from the number of product classes, so for DED the number of classes is equal to the number of products, for RAN, the number of classes is equal to one and for Class-Based storage the number of classes may range from two to the number of products minus one (Gu et al., 2007).

In a DED policy each storage location is reserved for a specific product, and no other product can be stored in that location. An advantage is that the storage locations can be memorized by pickers which can speed up the order picking process. Whereas in RAN, incoming products can be assigned to any empty storage location, which leads to a better occupancy rate of the warehouse. In Class-based storage, products are given a class based upon their popularity and the higher the popularity of the product, the closer it is stored to the I/O point (Ang, Lim, & Sim, 2012).

No Information

When there is no available information on the characteristics of the arriving items, it is called the storage location assignment problem based on no information (SLAP/NI), and only very simple storage policies can be used. The most frequently used are:

1. Closest-Open-Location (COL)
2. Farthest-Open-Location (FOL)
3. RAN
4. Longest-Open-Location (LOL)

The first two pick a location based on their distance from the I/O point and the last on the time a location has been vacant. According to Gu et al. (2007) it is not known if there is any significant performance difference between both policies.

3.3.2 Storage Assignment strategies

For the storage of products in the warehouse different strategies can be used to assign a location. These different strategies can be separated in two categories, DED and Shared storage. When using shared storage, new arriving product are assigned an empty location and therefore product locations will vary over time. To determine where a product is placed in the warehouse a number of policies can be used.

Random

When using the random storage assignment policy (RAN), products are assigned randomly to suitable, available locations anywhere in the warehouse. The storage utilisation of a warehouse will be higher than with DED as an empty storage location will be filled as soon as a new product arrives, and does not have to wait until a assigned product is replenished. However, this may lead to longer picking routes, as frequently ordered products are stored further away from the I/O point.

Cube-Per-Order Index (COI)

Cube-Per-Order Index (COI), which is the ratio of the maximum allocated storage space to the number of storage/ retrieval operations per unit time (Gu et al., 2007). This policy takes both the popularity of a SKU and its storage space requirement into account when assigning it to a location. Product is ranked by increasing COI and the classes with the lowest score are assigned the most favourable locations. Due to the popularity of certain items, it is possible that a large number of picking orders is located in a small area, causing order pickers having to wait for each other.

Class-Based

Class-Based storage assignment can be modelled as a two-stage process in which the product is first grouped in a product class, and then assigned a location within the area reserved for that class. In many warehouses, the popularity is distributed in such a way that 20% of the products account for 80% of the picking orders, which is also known as the *Pareto principle*. Using this knowledge, products are often divided in three classes (A, B, and C) where class A contains all fast moving products and class C holds the least popular items. These classes all have a certain area assigned to them in which the products are stored, and class A has the area that is the most accessible in the warehouse. As demand changes, it is necessary to review the different products in the warehouse and the classes they are assigned to after certain periods.

Duration of stay (DOS)

The DOS strategy is a class based storage assignment policy, but in contrast with the regular policy described in section 3.3.2 the classes are based on the individual unit load durations of stay rather than average product turnover rates (Goetschalckx & Ratliff, 1990). The downside is the amount of data required to uphold it, as the duration of stay has to be calculated for each individual item in the warehouse. It will however have a significant impact on the average distance required to travel by the order pickers, as the items that stay only for a short time are stored closest to the I/O point.

Affinity

When using a affinity based storage assignment strategy, products that are often ordered together are stored in the same area, to reduce picker travel time. This strategy assumes that orders are picked in a single picking tour and that there is no zoning or batching involved.

Fragmented

In a fragmented storage strategy, a product type can be assigned to multiple storage locations across the warehouse and picking orders can be completed from any of these locations. This allows for more order pickers being able to access the product and therefore the loads will be better balanced. Furthermore, it adds options for the routing assignment, as it has the choice of locations to pick from. It was found by Ho (2004) that this storage strategy works best for small orders with small pick quantities. When the quantities become to large, the possibility exists that multiple storage areas must be visited to complete the order, and therefore increase the distance needed to be travelled by the order picker.

Complex rules

Besides all previously mentioned strategies, it is possible to define a more complex decision making process that assigns the different products to storage locations. This type of strategy can use a number of different algorithms in the decisions it makes, and has the potential to learn from overrides of a warehouse manager. Modern WMSs collect such a considerable amount of data that there is a possibility that the storage strategy can be automated and the slower manual storage decisions will become obsolete (Kofler, 2015).

Summary

Warehouse storage can be divided in two basic categories, Dedicated Storage and Shared storage. Within these categories the decisions on the storage location assignment can be made according to a number of strategies. The strategies described are summarized in table 3.2 with a short description and their advantages and disadvantages.

3.3.3 Conclusion

The warehouse of Nijman/Zeetank as shown in figure 2.6 is divided in different zones that store different types of products, which are given in table 2.1. For each different product, separate rules apply and therefore for each zone a different Storage location assignment policy should be applied. The decision support system that is to be developed must be able to enable the manager to review the effects of the policy on the operational performance, helping him to make a decision.

Strategy	Description	Advantages	Disadvantages
Dedicated	fixed storage location(s) per product	low-tech, easy to implement, pickers can memorise locations	low storage utilisation
Random	storage location is randomly selected	frequently used in practice, performance baseline in many studies, easy to implement, balanced picker traffic, maximum space utilisation	longer picker tours
COI (Popularity)	position heavy and fast-moving products in favourable locations	easy to implement, optimal under certain conditions	congestion issues, part affinities not taken into account
Class based	assignment of products to classes (for example by popularity or value) following the 80 : 20 rule	frequently used in practice, less congestion if random storage is used within class	periodic review required, only reduces average picking tour length
DOS	Classes based on the individual duration of stay in the warehouse	shorter average picker travel	requires a considerable amount of data
Affinity	places parts, which are often ordered together, close to each other	shorter picker tours, higher throughput	potential congestion issues, algorithm parameter tuning
Fragmented	storage of items in multiple locations spread over the warehouse	increased availability, flexible picker routing and parallelisation, less congestion	lower storage utilisation, more complex picker routing
Complex rules	rule-based system learned from or tuned by human expert	more expressive, conditionals to accommodate different scenarios	algorithm parameter tuning

Table 3.2. Storage assignment policies (Kofler, 2015)

3.4 Decision Support System

This model should be applicable to not only the warehouse of Nijman/Zeetank in Poland, but also to other unit-load warehouses. To further improve the efficiency and effectiveness of the system, the decision support system must be able to help make the decisions on the tactical level and show their effect on the operational performance, which follows from sections 3.1.2 and 3.2.4. This section will describe different types of tools that can be used to do so.

3.4.1 Available tools

Linear programming

Linear Programming (LP) is a special case of mathematical optimisation whose requirements are represented by linear relationships. The most common type of application involves the allocation of limited resources among competing activities in a best possible way (Hillier & Lieberman, 2015). This optimisation dictates the amount of each resource that is to be allocated to the different activities, and can be applied to a wide range of situations. As the name states, all restrictions and relationships have to be linear, including the objective function. Linear programming is capable of representing large systems as long as all relationships are linear, and therefore *any* problem whose mathematical model abides by the rules of the very general format of the linear programming model is a linear programming problem. A general form of the model is:

$$\text{Maximize} \quad Z = c_1 x_1 + c_2 x_2 + \cdots + c_n x_n$$

subject to the restrictions

$$\begin{aligned} a_1 1 x_1 + a_1 2 x_2 + \cdots + a_1 n x_n &\leq b_1 \\ a_2 1 x_1 + a_2 2 x_2 + \cdots + a_2 n x_n &\leq b_2 \\ &\vdots \\ a_m 1 x_1 + a_m 2 x_2 + \cdots + a_m n x_n &\leq b_m, \end{aligned}$$

and

$$x_1 \geq 0, \; x_2 \geq 0, \; \ldots, \; x_n \geq 0.$$

Where Z is the value of overall measure of performance, x_j is the level of activity j (for $j = 1, 2, \ldots, n$), c_j is the increase in Z that would result from each unit increase in level of activity j, b_i is the amount of resource i that is available for allocation to activities (for $i = 1, 2, \ldots, m$) and $a_i j$ is the amount of resource i consumed by each unit of activity j (Hillier & Lieberman, 2015).

The function that is being maximized is called the objective function and the restrictions are referred to as the constraints. In linear programming the solution is not the final answer to a problem, here the term solution refers to all different values of the decision variables $(x_1, x_2, \ldots, x_n)$. When all constraints are then satisfied by the decision variables, a feasible solution is found, if not, it is an infeasible solution. The collection of all feasible solutions is called the feasible region, and within that region lies the optimal solution, which is a feasible solution that has the most favourable value of the objective function.

As a decision support model, a linear programming model is useful at the strategic and tactical levels, due to its linear nature. On an operational level it is less suitable as it is a deterministic way of modelling systems, whereas in real life, in- and outbound flows are stochastic and vary considerably on a day-to-day basis.

Integer programming

Where in linear programming al decision variables are able to be any real positive value, there are cases in which the decision variables only make sense if they have integer values, when they depict the number of people or machines assigned to an activity. When this is the only difference between the problem and a linear programming formulation, it is an Integer Programming (IP) problem. As with the LP, the IP is most suited for strategic and tactical decision making, also due to the fact that it is a deterministic way of modelling systems.

The integer programming model uses the same mathematical model as the linear programming model with the additional constraint that all variables must have integer values. Some types of integer programming have more special rules apply to them:

Binary Integer Programming (BIP) In certain applications of the integer programming, the decision variables represent a number of interrelated *yes-or-no* decisions. In these decisions there are only two possible choices, *yes* and *no* that are represented by a value of 1 or 0.

Mixed Integer Programming (MIP) Here the mathematical model of linear programming is used with the extra constraint that some of the variables must have integer values.

Queueing Theory

Queueing theory is the mathematical study of queues, or waiting lines. Using this theory a model of a system can be made which has the following structure: Customers arrive and join a queue to await service by any of several servers. After receiving service the customers depart the system. The queueing theory can be used to calculate the optimal capacity of a warehouse using Little's Law. Little's law can be used to calculate one of three variables when the other two are known and is shown in equation 3.3

$$L = \lambda \cdot W \tag{3.3}$$

With L as the average number of elements in queue, λ is the mean response time and W the waiting time in a queue. These variables can be used to represent the different aspects of a warehouse, this means that L is the average number of products in the warehouse, λ the average time it takes to move a product from the inbound position to a storage location and to an outbound position and W the average time a product spends in the system. With these descriptions it is possible to calculate the highest possible throughput for a warehouse, as it does not account for dead-heading or re-stacking to reach products. It becomes clear that queueing theory is a fitting tool for the strategic and tactical decisions, but lacks the detail required for the prediction of the performance on an operational level.

As an example the capacity of a warehouse will be determined using Little's law. This warehouse has the input variables shown in table 3.3.

Number of pallet positions	10.000
Average time to move a pallet	6 minutes
Number of turns per year	4
Hours in a day	8 hours
Days in a year	250 days

Table 3.3. Example of Little's law used to calculate warehouse capacity

The question is: *'what labour force is necessary to support this?'* Using Little's law it follows that:

$$10.000 \text{ pallets} = \lambda(1/4 \text{ year})$$

so that

$$\lambda \approx 40.000 \text{ pallets/year}$$
$$\lambda \approx 20 \text{ pallets/hour}$$

Which is an estimate for the labour force required in the warehouse, with an occupancy of 100 %, simply from counting the pallet positions and estimating the number of turnarounds per year.

Simulation

In simulation a computer is used to imitate the operation of an entire process or system over a period time. In order to perform a simulation, the selected physical or abstract system must first be modelled, which is a representation of the characteristics and functions of the system. The difference between a model and a simulation is that the model represents the structure, whereas a simulation represents its behaviour. When a real-life or hypothetical situation is modelled as a computer simulation it is possible to study the situation and gain an understanding in the workings of the system. It is possible to make changes to certain variables which can be used to predict the behaviour of the system. With these characteristics in mind, it is clear that simulation is a tool that allows researchers to virtually investigate the behaviour of a system. Simulation is a tool that can be applied in a number of different ways, some are described below.

Static/Monte Carlo Simulation A static simulation is a simulation that is not based on time and often involves drawing random samples to generate a statistical outcome (Harrell, Bowden, & Ghosh, 2000). Because of this random nature, such simulations are referred to as Monte Carlo simulations and are often used in simulating physical and mathematical systems. When it is unfeasible or impossible to compute an exact result with a deterministic algorithm, this type of simulation is found to be useful.

Continuous Simulation The main distinction of this type of simulation is that it describes how a simulated component responds when subjected to various conditions in a finite time span with an infinite amount of state changes. By making extensive use of mathematical expressions, these state changes are described in complete detail (Craig, 1996). By combining differential and algebraic equations the variance of the individual variables can be expressed over time, as well as their relationships (Fayek, 1988).

The input variables of a continuous model are expressed as differential equations, as these are influenced by the environment over time. The relationship between the input and the output variables is described using algebraic equations. When simulating, these equations are applied in the context of the components environment and connectivity and produce a continuous graph that accurately reflects how the components were to react in reality. The use of these equations has the potential to increase the need for computational resources, especially when a large number of elements are present that are related.

Discrete Event Simulation A discrete event simulation models the operation of a system as a discrete sequence of events in time. This means that at certain times events take place that mark a change of state in the system and it is assumed that between these events the state does not change. Due to this assumption, the simulation is able to jump to the next scheduled event, leaving the time in between unchanged. By skipping the time in between events and only changing the state of the elements that triggered the event, discrete event simulation is able to handle the simulation of systems with a large amount of components. Even when the number of components is high, the simulation is fairly quick and will be able to provide a reasonably accurate approximation of a system's behaviour (Craig, 1996).

Hybrid Simulation In a hybrid simulation the characteristics of both the continuous simulation and the discrete event simulation are combined, creating the possibility to have both continuous-change and discrete-change state variables. Most processing systems have both types of variables. For example, a truck or a tanker arrives at a fill station, a discrete event, and begins filling a tank, a continuous process.

There are four basic interactions between discrete- and continuous-change state variables (Harrell et al., 2000):

1. A continuous variable may suddenly increase or decrease as the result of a discrete event (like the sudden replenishment of inventory in an inventory model)
2. The initiation of a discrete event may occur as the result of reaching a threshold variable in a continuous variable (like reaching a reorder point in an inventory model)
3. The change rate of a continuous variable may be altered as the result of a discrete event (a change in inventory usage rate as the result of a sudden change in demand)

4. An initiation or interruption of change in a continuous variable may occur as the result of a discrete event (the replenishment or depletion of inventory initiates or terminates a continuous change of the continuous variable)

Simulation can be used to describe systems on all three levels (Strategic, Tactical and Operational) of decision making, and has some variances, such as discrete event simulation, that are capable of showing the effects of a high level decision on a lower level. An advantage of simulation is that it is capable of modelling the supply and demand of a model stochastically. This allows for a simulation to give a more realistic representation of the system, due to the fact that product never flows as a fixed number over the same time period.

Chapter 4

Model selection

As NSG Pilkington is scaling up production this leads to an increase in the demand for the logistical services provided by Nijman/Zeetank. This increase in throughput and customer service level in the warehouse is to be realised without increasing the number of resources, and preferably even reducing them.

The warehouse is operating in an existing building using forklifts to move the product. This means that the decisions on the strategical level are already made, so the increase in the throughput and customer service level have to be made by decisions on the tactical level. These decisions regard the assignment of storage space and the allocation of forklift time, or in different terms, the use of resources. To assist a warehouse manager in making these decisions, he needs to be able to see the effects of his decisions and therefore a decision support system, or tool, is to be developed. The tool will help to answer the main research question:

> *How are the forklifts and storage area of Nijman/Zeetank in Chmielów to be used to meet the expected increase in demand from NSG Pilkington in an efficient and effective way?*

In order to help the manager, the tool needs to be able to vary the use of the resources based upon the supply and demand of products and on different resource allocation policies. When the resources are divided, the tool must be able to show their effect on the operational performance, upon which the warehouse manager can base his decisions. This chapter will also aim to answer the following research question:

5. What kind of decision support system is most suited for this problem?

4.1 Input

The input of the model consists of the warehouse and the different policies concerning the utilisation of the resources. For the warehouse it starts with the walls, and its resources, such as the storage lanes and the forklifts. The model interacts with the environment through the production lines and the trucks, which give a certain supply and demand of product. This supply and demand is found to be a distribution with a mean and a standard deviation. These elements all have properties that influence the behaviour of the model, some of the possibilities are given below:

Warehouse layout

- Storage lanes
- Transfer zones for the Production lines
- Staging areas for the shipments

Control/logistics

- Supply and demand distribution
- Forklift time allocation
- Storage location assignment

Forklifts

- Speed
- Capacity
- Size

For the policies, the input will consist of different sets of rules that dictate how the resources are to be used. Examples of these rules are:

- Single cycle for the forklifts
- Dual cycle for the forklifts
- Random storage
- Use of zones

4.2 Required number of forklifts

The required number of forklifts is found to be dependent on two factors, namely the time required per SKU and the number of SKUs. Using these two factors, the following equation is constructed:

$$n_{forklift} = \frac{\bar{T}_{servicetime,SKU} \cdot \bar{n}_{SKU}}{T_{op}} \tag{4.1}$$

Where $n_{forklift}$ is the number of forklifts, $\bar{T}_{servicetime,SKU}$ the mean handling time for 1 SKU, $\bar{n}_{SKU}$ the total number of SKUs, and T_{op} the total operational time of all forklifts. When the complexity of the model increases, the more complex equation 4.2 is constructed, as each SKU has a different location and therefore requires a different amount of time to service.

$$n_{forklift} = \frac{\sum_{i=1}^{n_{SKU}} T_{servicetime,SKU}}{T_{op}} \tag{4.2}$$

In reality the $T_{servicetime,SKU}$ is divided in different parts as described in section 2.6 and therefore the equation becomes:

$$n_{forklift} = \frac{\sum_{i=1}^{n_{SKU}} \sum_{j=1}^{p} T_{servicetime,i,j}}{T_{op}} \tag{4.3}$$

Equation 4.3 adds the different periods of time it takes to complete p parts of the service of an SKU, and adds the total service times of all SKUs to calculate the required number of forklifts. To be able to use equations 4.1, 4.2, and 4.3, the number of handled SKUs and the service time per SKU must be known.

To determine the required complexity of the model, a distinction is made ranging from a simple model to a complex simulation. In this distinction the consequences for three different properties are shown. These three properties are:

A The available information on the SKUs
B The servicetime $T_{servicetime,SKU}$ per SKU
C The number of SKU handled by the warehouse n_{SKU}

Simple model

$$\text{Number of forklifts} = \frac{\bar{T}_{servicetime,SKU} \cdot \bar{n}_{SKU}}{T_{op,i}}$$

A No information is known about the specific SKU, only the amount
B Service time is constant and is based on an average value
C The number of SKUs is constant and is based on an average value

$$\text{Number of forklifts} = \frac{\sum_{i=1}^{n_{SKU}} T_{servicetime,SKU}}{T_{op,i}}$$

A Information about the specific SKU is known
B Service time is based on the SKU, constant value for each location
C The number of SKUs differ based on a distribution

$$\text{Number of forklifts} = \frac{\sum_{i=1}^{n_{SKU}} \sum_{j=1}^{p} T_{servicetime,SKU}}{T_{op,i}}$$

A Information about the specific SKU is known
B Service time is measured and based on the movements of a forklift
C The number of SKUs differ based on a distribution

Complex Simulation

On the scale above three different models are given, however, these are not the only possibilities. The amount of possibilities are numerous, as new possibilities arise by changing the properties.

4.3 Model

All product flow inputs are given as a mean value with a standard deviation, as the data used consists of all SKU movements separated per day of 2015. Furthermore, the in- and outbound trucks are also given by a distribution, as the number of trucks arriving and departing per day was measured over the course of the entire year. Due to the fact that all state changes in the system are triggered by a stochastically defined supply and demand, a discrete event simulation will be developed to simulate the warehouse and calculate the operational performance.

Chapter 5

Conceptual Model

This chapter describes the conceptual model using the model boundaries, the assumptions made and a brief overview of the performance indicators and will identify the Key Performance Indicators (KPIs). At the end a plain text overview of the model and its processes is given.

5.1 System boundaries

The model is used to simulate all SKU movements within the warehouse using the supply and demand of the different clients of the warehouse, where the supply and demand can be continuous or in batches. This is done by simulating the forklifts moving in the warehouse and encompasses all driving, the picking and the putting away of the SKUs. The model is capable of simulating any warehouse with any number and type of forklifts.

The model uses staging lanes for clients that have demand in batches, and it will free all SKU that belong to a outbound batch at the delivery time. The actual loading of the batch is left outside the system boundaries.

5.2 Assumptions

The following assumptions were made:

- For all SKUs the Item Information is known (section 3.3.1)

- All forklifts move only one SKU at a time.

- There are only two types of containers in the warehouse, metal containers that can be stacked up to three high, and wooden containers that can be stacked two high.
- All containers can be picked and moved by all forklifts.

To increase the efficiency in the storage and order-picking operation, it is assumed that the warehouse has a Warehouse Management System (WMS) that is capable of giving real-time information and individual tasks to the forklift drivers. This leads to a reduction of time spent driving to a supervisor and receiving orders either verbally or on paper.

The forklifts move only one SKU at a time as most SKUs are too heavy to be moved in larger numbers. Furthermore, due to the size of the actual container, the visibility of the driver will be obstructed if more than one SKU is moved, which reduces safety. The simulation uses only two types of containers whereas there are many more different types. This reduces the work that needs to be done with regard to the storage, compared to the reality.

In the model it is possible for all forklifts to pick all SKUs, whereas in reality some containers are either too heavy or not deep enough for a forklift. This reduces the amount of work as certain tasks will not need certain forklifts to complete them.

5.3 Key Performance Indicators

Section 3.1.2 gives the following list of performance indicators:

- Orders
  - Performed tasks per hour
  - Task lead time
  - Released tasks
- Products
  - Moves per hour
- Resources
  - Forklift utilisation
  - Storage area utilisation
  - Unnecessary movements

As the warehouse provides a service, the storage and delivery of SKUs to a destination at the system boundaries at a certain time, it is key to deliver all SKUs on time (before the production needs the SKU or the shipment needs to depart). To achieve this the storage and retrieval tasks should be executed in a timely manner, therefore the task lead time is chosen as a Key Performance Indicator (KPI).

Furthermore the main research question stated in chapter 4 that the resources, the forklifts and the storage area, should be used in an efficient and effective way. As most warehouses using Item Information (section 3.3.1) are able to store the SKUs in an efficient way such that honeycombing (figure 3.5) is kept to a minimum, the storage area utilisation is chosen not to be a KPI. The forklift utilisation is set as a KPI and will be separated according to the distribution described in section 2.6.

5.4 The model

The conceptual model contains a process oriented description of the model in plain language. The element classes in the model are: Forklift, SKU, Storage, Staging, Node, Arc, Product, Transfer zone, Task, Zone, Batch, WMS and Forklift Management. Each of these element classes have their own properties such as location, size, supply, demand etcetera. These attributes are listed in the Process description model that can be found in appendix E.1.

5.4.1 Processes

Within the model there are a number of elements that have their own processes and some functions that determine where a SKU is headed and where it should be stored. These processes and functions will be described briefly below and in more detail in appendix E.2.

- Function Storage location

  Zones

    Check zone for available storage locations

    Select MyStorage location

    Result is MyStorage

  Near Destination

    Check for available storage locations near the destination

    Select Mystorage location

    Result is MyStorage

  Near Origin

Check for available storage locations near the origin

Select Mystorage location

Result is MyStorage

- Function Destination

  Check all Clients for demand for this product type

  Calculate probability for destinations

  Generate random number between 0 and 1

  Select destination based on random number and probabilities

- Client

  Supply

  if Client is not in batch then

  CreateSKU

  Hold for $\left(\frac{24 hours}{\text{number of SKU per day}}\right)$

  else if Client is in batch then

  Number of SKU = SKUIn.Sample

  for SKUSample do

  Select Product type

  CreateSKU

  Hold for $\left(\frac{24 hours}{\text{number of batches per day}}\right)$

  Demand

  if Client is not in batch then

  Select next inbound SKU

  Hold until one hour before deliverytime

  Create retrieval task

  else if Client is in batch then

  See Batch

- Forklift

  Process

  - Drive to start
  - Pick up SKU from storage or transfer zone
  - Drive to destination
  - Put SKU in storage bin, staging lane or transfer zone
  - Resume Forklift management

  Drive

  Node1 is first element of Route

  for length of Route do

Node2 is successor of Node1 in Route

Select Arc between nodes

Hold $\left(\frac{ArcLength}{Forkliftspeed}\right)$

Remove Node1 from Route

Node1 is Node2

- Batch

  Check if all SKU are present

  if FALSE then

  Create Rush SKU

  Hold until all SKU are present

  Free all SKU in batch

- WMS

  Sort all tasks on time in TimeQ

  Select first task from TimeQ

  Hold until Releasetime

  Remove Task from WMStaskQ

  Add Task to TaskQ

  Resume Forklift management

- Forklift management

  Wait until there are Tasks in TaskQ

  Wait until there are Forklifts in ForkliftQ

  Mytask is first element in TaskQ

  Select Forklift based on distance

  Resume Forklift

5.4.2 Input

This section will describe the different parts used to create the virtual warehouse, the operations and what rules apply to the decisions made on the operational level.

Warehouse

To create the warehouse for the simulation, the first thing that needs to be done is to create the nodes that are used to define the routes driven by the forklifts. The information required is stored in a text file in the format as shown in table 5.1. The next step is to create the transfer zones, again the information is stored in a text file according to the same format as for the nodes. Following are the storage bins and the staging lanes, with the information stored in a text file as shown in table 5.3. The dX and dY values represent the width and length of the storage bin or the staging lane, and the X and Y values represent a corner point. The final two parts of the warehouse are the walls, that are primarily used for the animation, and the arcs on which the forklifts move to transport SKUs through the warehouse. The walls are drawn using information from a text file that contains a starting and an end point divided into X and Y values. The arcs are constructed using information from a text file that contains the arc number and both of the nodes it is connected to as can be seen in table 5.2. When all this data has been processed the model is able to draw the warehouse as shown in figure 5.1.

Node number	X [m]	Y [m]
1	146,3	30,5
2	146,3	28
3	146,3	24,9
4	170,1	30,5
5	170,1	28

Table 5.1. Excerpt of the Node input file

Arc	Node 1	Node 2
1	1	A01
2	1	2
3	2	A02
4	2	3
5	3	A03

Table 5.2. Excerpt of the Arc input file

Storage/Staging	X [m]	Y [m]	dX [m]	dY [m]
W01	6,6	91,2	2,9	7,4
W02	9,5	91,2	1,8	7,4
S1	35,8	18,6	2,0	-10,8
S2	38,3	18,6	2,0	-10,8

Table 5.3. Excerpt of the Storage bin or Staging lane input file

Operation

After creating the warehouse, the operation should be defined, which encompasses the products handled by the warehouse, the clients that supply and request these products, the forklifts that move the SKUs and the outgoing batches.

The products are loaded from a text file that has information about the distribution of daily stock of that product and how much of that product is stored in the different types of containers. An example of this text file is shown in table 5.4.

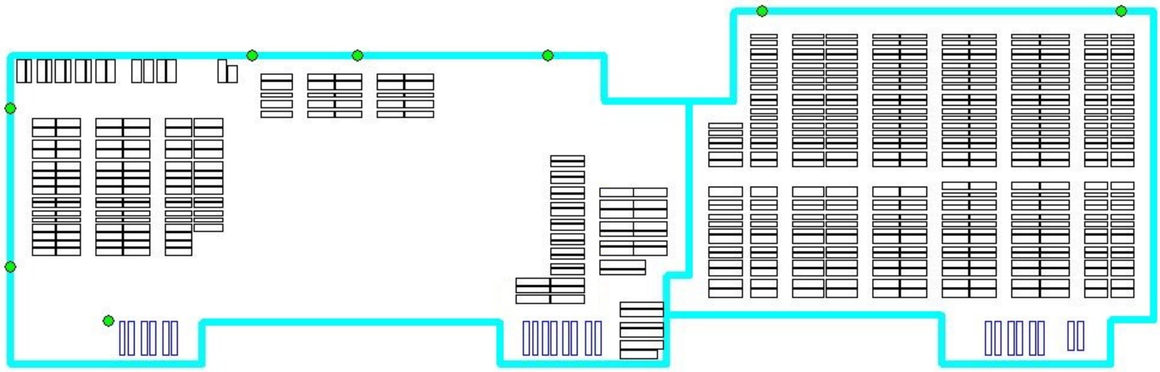

Figure 5.1. Virtual empty warehouse

The clients are loaded with data about their Transfer Zone (TF), if the client supplies and demands product in batches, and if so, the frequency and number of SKU in those batches. An example of this data is shown in table 5.5. Furthermore the text file contains the supply and demand of the separate clients per product, which can be loaded from this file or from a separate file that has an historical overview of the supply and demand, divided into daily numbers.

The next step is to create the forklifts, again using a text file, which contains information about the width, length, the capacity and the length of the forks. An example of this data can be found in table 5.6.

When the entire operation is loaded it is possible to either create or load a starting stock. The loaded stock is created using the program and saved in text files that correspond with the storage bins. In these files data is stored about the origin and the destination of the SKU and the delivery times. Furthermore the product type and the stack height are recorded, as well as the container type, an excerpt of this data is shown in table 5.7.

The final part of the operational input is a schedule for the batches, including the delivery time, the total amount of SKUs in the batch, the amount of SKUs per product type and the staging lane where all products are collected before the delivery time. This is illustrated in table 5.8.

Product	Mean stock	σ_{stock}	% wood	% metal
Raw	879	65	0	100
WIP	6502	308	0	100
Finished product	3175	313	79	21

Table 5.4. Excerpt of the Product input file

Name	TF_{in}	TF_{out}	Batch	$Batch_{in}$	$\sigma_{batch,in}$	SKU_{in}	$\sigma_{SKU,in}$	$Batch_{out}$	$\sigma_{batch,out}$	SKU_{out}	$\sigma_{SKU,out}$	$Product_{in}$	$\sigma_{product,in}$	$Product_{out}$	$\sigma_{product,out}$
Trucks	truckin	TF4	true	19	6	20	11	22	3	25	20	296	105	203	75
1	TF1	TF2	false									0	0	84	38
2A	TF3	TF5	false	0	0	0	0	0	0	0	0	76	56	124	58
2B	TF6	TF7	false	0	0	0	0	0	0	0	0	114	68	73	39

Table 5.5. Excerpt of the Client input file

Forklift	Width [m]	Length [m]	Capacity [kg]	Forklength [m]
1	1,17	3,365	2500	1
2	1,17	3,365	2500	1
3	1,17	3,365	2500	1

Table 5.6. Excerpt of the Product input file

Storage Policy

To determine where to store a SKU a certain storage policy must be chosen. For this model three different options are chosen based on the information given in section 3.3. Because it is assumed that all information about all SKUs is known, within each storage policy all SKU are stored based on their delivery time. This means that the SKU at the front of a storage bin always has to be delivered before the SKU behind it, and when it is not possible to find such a storage location, the SKU will be stored in front of an SKU with a delivery time as close as possible to the delivery time of the SKU that is to be stored.

An example of this is shown in figure 5.2, here Forklift 1 needs to store SKU3 that needs to be delivered at 22:00h and there are two storage bins available. The first storage bin contains only SKU1 that needs to be delivered at 21:00h, and the second contains only SKU2 that has a delivery time of 23:00h. To be able to deliver all SKUs on time without any double movements, SKU3 is placed in front of SKU2, so that it is removed before SKU2 has to be picked.

The first option for the storage policy is based on the current situation in the warehouse of Nijman/Zeetank, which is a zone based storage policy, where each zones is designated to a product type. Within these zones a random storage policy is used, so therefore each SKU can be stored in any position, keeping in mind the restrictions mentioned above. The second and third storage policy are derived from a combination of random and Class-based storage(section 3.3.2). The only difference between the two policies is location of the favourable storage locations, as one of these policies sees the favourable locations near the destination of the SKU, and the other near the origin.

SKU	Origin	Destination	Product type	Delivery time	Stack height	Container
SKU2242	truckin	2A	WIP	31.967,1	1	Metal
SKU2247	truckin	2A	WIP	31.997,0	0	Metal
SKU2250	truckin	2A	WIP	32.011,7	2	Metal
SKU2253	truckin	2A	WIP	32.020,3	1	Metal
SKU2256	truckin	2A	WIP	32.033,9	0	Metal
SKU2260	truckin	2A	WIP	32.058,8	2	Metal
SKU2262	truckin	2A	WIP	32.065,1	1	Metal
SKU2265	truckin	2A	WIP	32.091,4	0	Metal
SKU2267	truckin	2A	WIP	32.094,6	2	Metal
SKU2271	truckin	2A	WIP	32.123,5	1	Metal

Table 5.7. Excerpt of the stock input file

Batch	Delivery time	Total SKUs	Staging lane	Product	SKU	Product	SKU	Product	SKU
45	2.939,8	5	S1	Raw	0	WIP	3	FP	2
46	3.019,6	5	S2	Raw	0	WIP	3	FP	2
47	3.086,4	9	S3	Raw	0	WIP	5	FP	4
48	3.149,5	29	S4	Raw	0	WIP	7	FP	22
49	3.208,7	33	S5	Raw	0	WIP	16	FP	17
50	3.270,9	26	S6	Raw	0	WIP	16	FP	10
51	3.330,7	37	S7	Raw	0	WIP	21	FP	16
52	3.404,1	36	S8	Raw	0	WIP	22	FP	14
53	3.466,9	2	S9	Raw	0	WIP	1	FP	1
54	3.551,2	51	S10	Raw	0	WIP	38	FP	13

Table 5.8. Excerpt of the batch input file

5.4.3 Output

The output of the model consists of a number of text files that can be put into two different categories, the first involves the tasks that were released into the warehouse, and the second the work done by the forklifts. The different parts of the time spend working are described in section 2.6.

Task

Two of the text files that are created by the model concern the tasks, one contains all unfinished tasks, and the other contains all completed tasks, with the task number, the type of task, the time it was released into the warehouse operation, and the time it was completed. Using these times a task lead time can be calculated, which is according to section 5.3 a KPI. An example of this output file including the calculated lead time is shown in table 5.9.

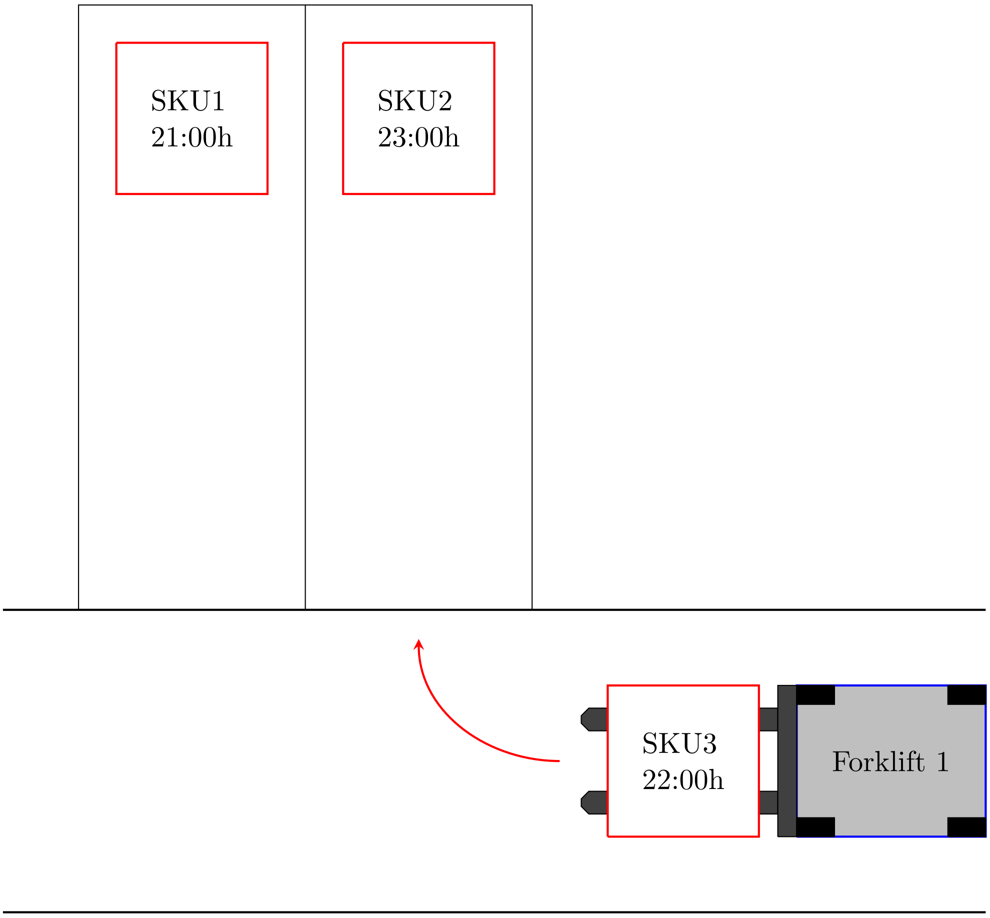

Figure 5.2. Forklift 1 has to store SKU3

Forklift utilisation

The second KPI from section 5.3 is the utilisation of the forklifts, which is divided into a number of different activities. These activities only concern the actions needed to complete the tasks, unlike the activities described in section 2.6, where the activities are described that involve the searching and extraction of the SKU from their storage locations. The utilisation of the forklift is divided in the following parts:

- Empty driving
- Pick time
- Loaded driving
- Put away time

Task	Release time	Completion time	Type	Lead time
Task000000005121	538,78	561,34	Retrieve	22,56
Task000000005120	538,78	561,36	Retrieve	22,58
Task000000005966	540,07	561,41	Store	21,34
Task000000005122	538,78	561,81	Retrieve	23,03
Task000000005124	538,78	562,20	Retrieve	23,42
Task000000005969	545,85	562,23	Store	16,38
Task000000005123	538,78	562,30	Retrieve	23,52
Task000000005968	543,76	562,52	Store	18,76
Task000000005125	538,78	563,07	Retrieve	24,29
Task000000005126	538,78	564,19	Retrieve	25,41
Task000000005971	552,68	565,28	Store	12,6
Task000000005976	563,22	565,35	Store	2,13

Table 5.9. Excerpt of the Task output file

T_{now}	T_{worked}	% worked
659,47	5080,17	51,356
659,49	5080,21	51,355
659,51	5080,25	51,354
659,51	5080,48	51,356
659,51	5080,50	51,356
659,53	5080,52	51,355
659,55	5080,56	51,354
659,57	5080,60	51,353
659,57	5080,63	51,353
659,60	5080,66	51,351

Table 5.10. Excerpt of the worked time output file

The model creates a text file for each part of the forklift utilisation and one for the total time that the forklifts spend working. These text files all contain lines with two values, the first value is the point in time at which point the data was recorded, and the second value is the total time spent doing that activity for all forklifts combined. For the analysis, this last value is divided by the first value multiplied by the total number of forklifts, or:

$$\text{Worked time \%} = \frac{T_{worked}}{T_{now} \cdot n_{forklifts}} \tag{5.1}$$

This equation is repeated for each line. And after removing the initial peak from the simulation, an average percentage of the total time spent is calculated. An example is shown in table 5.10.

Chapter 6

Simulation

After using all the input data described in section 5.4.2 the simulation is started. This will trigger a number of events starting with the WMS, which will release tasks into the warehouse for forklifts to execute. After the tasks have been released the Forklift management assigns different tasks to the forklifts based on the shortest distance between the start point and the current location of the forklift. Then the forklift begins to move to the starting point of the task, at which moment he begins to record the time he spend working on this task. The time he spends moving toward this location is also stored as empty driving or dead-heading time. When he arrives at the starting location of the task, he searches the storage area or transfer zone for the SKU he is meant to move and picks it up, which takes a predefined amount of time, based on the stack height of the SKU. This time is recorded as the picking time. With the SKU loaded on the forks, the operator steers the forklift to the destination of the SKU and the simulation records his time as loaded driving time. Upon arrival at the destination the forklift puts the SKU away, which requires a predefined amount of time based upon the stack height of the SKU, the same as with the picking, and stores it as the put away time. When the SKU has been stored the working time stops and it is stored. All these times are stored in the files described in section 5.4.3.

When the tasks are released into the warehouse, that moment of time is saved with the task in order to calculate the lead time. When the forklift finishes his task, that time is also saved with the task. At the end of the simulation this information is stored in the files described in section 5.4.3

6.1 Verification

To verify if the model is implemented correctly, a number of checks were done both with the output of the system and during runtime. During runtime the events that occurred in the simulation were traced and compared with how they would be executed according to the rules set. The output was first used to do a balance check on the worked time of the forklifts, to make sure that all the time spent working is also accounted for in the different activities described in 5.4.3. Furthermore it was used in a capacity calculation to find the required number of forklifts to move the average amount of SKUs with the average driving distances.

6.1.1 Event Tracing

To do the event trace, the simulation was loaded with the warehouse of Nijman/Zeetank and an operation with a stock of 100 SKU in the warehouse and three SKU coming in from three different transfer zones. These SKUs were all of a different product type and due to the storage policy selected (Zones) they should all be stored in a different zone in the warehouse. The Forklift starts at node 1. The first task is to pick SKU 'Rawverify' from transfer zone TF1, and store it in storage 'W01', which is the first storage location in zone 'W', which is designated for SKUs of type Raw. The forklift starts moving along the calculated shortest path to transfer zone TF1, as is displayed in figure C.1.

After picking SKU 'Rawverify' from TF1, the forklift moves to 'W01' along the route shown in figure C.2. The SKU is stored and suspends awaiting a new task from the Forklift management. As there are still SKUs waiting to be stored the forklift immediately is assigned another task which is to pick SKU 'WIPverify' from transferzone TF6 and store it in storage 'A01', which is in zone 'A'. This is the correct zone as it is designated for SKUs of product type WIP. Again the forklift moves from its current location to the start of the task, picks the SKU and stores it in storage 'A01'.

The next task is the storage of SKU 'FPverify', which needs to be picked from transfer zone TF4 and stored in storage 'S001'. The forklift moves to TF4 to pick up the SKU, and stores it in 'S001'. To verify if the simulation moves through all the steps in the correct order and that the times measured are correct, the routes taken are shown in appendix C.1 including the time calculations for those routes. These results are compared with the values of the trace function of the simulation in table 6.1. The table shows both the calculated and the simulated times of when the forklift arrives at the nodes, from which can be seen that these are the same.

Route	Calculated Arrival Time [min]	Simulated Arrival Time [min]
Node 1 to TF1	1,94	1,94
TF1 to W01	4,22	4,22
W01 to TF6	7,95	7,95
TF6 to A01	9,99	9,99
A01 to TF4	11,36	11,36
TF4 to S001	13,05	13,05

Table 6.1. Arrival times from the trace verification

6.1.2 Balance check

The balance check is done by adding up the time spent working on the different activities and checking if these add up to the total time spent working. This is done using the output files of the Nijman/Zeetank warehouse simulation with the Near Origin policy and the number of forklifts working on the operation ranging between 3 and 14. The averages per activity of all operations are shown in table 6.2. The table shows a difference between the total and the measured working time of 7,9 minutes, which is caused by averaging the values for each activity, this is a difference of only 0,1%.

Activity	Time spent [min]	Time spent [%]
Empty driving	2.799,0	40,49
Pick up	270,5	3,85
Loaded driving	3.607,3	51,51
Put away	301,3	4,27
Total	6.978,1	100,10
Worked time	6.970,2	

Table 6.2. Working times and their distribution

6.1.3 Capacity calculation

To calculate the required number of forklifts for the warehouse, $n_{forklift}$, the total worked time T_{work} and the total idle time T_{idle} are divided by the number of net operational minutes in a day (equation 6.1). In this capacity calculation, the idle time T_{idle} is set to 0 minutes.

$$n_{forklift} = \frac{T_{work} + T_{idle}}{1320 \text{ [min]}} \tag{6.1}$$

The total worked time is calculated by multiplying the mean handling time for 1 SKU $\bar{T}_{servicetime,SKU}$ with the average number of SKUs n_{SKU}. The $\bar{T}_{servicetime,SKU}$ is calculated by adding the time required to perform all steps to perform a task. This includes the time spent driving towards the SKU ($\bar{T}_{dead-head}$), picking it ($\bar{T}_{pick}$), driving it to its destination ($\bar{T}_{driving}$) and putting it down ($\bar{T}_{put}$) (equation 6.2).

$$\bar{T}_{servicetime,SKU} = \bar{T}_{dead-head} + \bar{T}_{pick} + \bar{T}_{driving} + \bar{T}_{put} \quad (6.2)$$

For this calculation it is assumed that the warehouse operates under full single cycle, as almost 60% of all SKUs has its origin or its destination with the trucks and there will be moments when it is not possible to perform dual cycle operations. Therefore:

$$\bar{T}_{dead-head} = \bar{T}_{driving}$$

$\bar{T}_{driving}$ is calculated by dividing the average driving distance from or to a client ($\bar{s}_{driving}$) by the speed of the forklifts ($v_{forklift}$). $\bar{T}_{pick}$ and $\bar{T}_{put}$ are measured in the warehouse in Chmielów and the average values are used in this calculation. All values can be found in table 6.3.

Description	Value	Unit
$\bar{s}_{driving}$	196,90	m
$v_{forklift}$	83,30	m/min
$\bar{T}_{pick}$	0,25	min
$\bar{T}_{put}$	0,27	min
n_{SKU}	1422	SKU

Table 6.3. Input values for the capacity calculation

Using these values $\bar{T}_{driving}$ becomes:

$$\bar{T}_{driving} = \frac{\bar{s}_{driving}}{v_{forklift}} \quad (6.3)$$
$$\bar{T}_{driving} = \frac{196,9 \text{ [m]}}{83,3 \text{ [m/min]}}$$
$$\bar{T}_{driving} = 2,37 \text{ [min]}$$

Using equation 6.2 the following $\bar{T}_{servicetime,SKU}$ is found:

$$\bar{T}_{servicetime,SKU} = 2,37 + 0,25 + 2,37 + 0,27 \text{ [min]}$$
$$\bar{T}_{servicetime,SKU} = 5,24 \text{ [min]}$$

T_{work} then becomes:

$$T_{work} = \bar{T}_{servicetime,SKU} \cdot n_{SKU} \tag{6.4}$$
$$T_{work} = 5,24 \text{ [min]} \cdot 1422$$
$$T_{work} = 7451,28 \text{ [min]}$$

Entering this into equation 6.1 leads to the following required number of forklifts:

$$n_{forklift} = \frac{7451,28 \text{ [min]}}{1320 \text{ [min]}}$$
$$n_{forklift} = 5,6$$

This gives the minimum required number of 6 forklifts, which does not take into account periods of time in which there are no tasks to be done, therefore leaving the forklifts standing idle.

6.1.4 Runtime visualisation

During the simulation there are two types of visualisation, the first is a graph that shows the percentage of time worked, the amount of unassigned tasks in the warehouse and the amount of working forklifts. The second visualisation is a map of the warehouse which contains all storage lanes, their fill rate depicted by a part of the storage area coloured red, the staging lanes and the forklifts. The forklifts are animated and are shown to move around the warehouse in three different colours, blue when they are waiting, yellow when the are driving empty and green when moving with a SKU. When looking at the visualisations it is visible what is happening in the warehouse and how the forklifts react to the different situations.

6.1.5 Conclusion

Following the event trace from section 6.1.1 and the balance check of section 6.1.2 it is made clear that the model is successfully implemented. Using the runtime visualisation, it is possible to identify pressure points, or areas with congestion, in the warehouse and how long it takes for peaks in the number of tasks to be completed.

6.2 Validation

The definition of validation is *'substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model'* (Sargent, 2005). To be able to draw any conclusions concerning the validation of the model, this section will be divided into three parts:

- Input
- Model assumptions and processes
- Experimental results

6.2.1 Input

All input figures are based on historical data concerning the movements of SKUs in the warehouse over the year 2015. Most input values that were used to create a distribution in the model were combined as a data file with all data present to increase the accuracy, instead of putting them in the form of a normal distribution. Those values that were put in as a normal distribution did show a behaviour that resembled a normal distribution. Furthermore measurements were done regarding the time it takes for a forklift to pick up and put down a SKU on different heights and with different forklift operators. Besides it was measured for 544 SKUs how long it took to locate and flag them.

6.2.2 Assumptions and processes

Section 5.2 describes all assumptions and their effect on the outcome of the experiments. These effects are difficult to quantify due to the fact that there is no data to be found regarding a unit-load warehouse using this system for all the movements in the building. In section 5.4.1 all processes of the simulation model are described and when these are compared to the reality as described in chapter 2, it is clear that the model follows the same steps as the reality.

6.2.3 Experimental results

From the results of the experiments in chapter 7 the simulated time spent working can be found, which is presented in table 6.4. According to table 2.6 the current time required to move a SKU in a single cycle operation is 4,88 minutes (SKU movement and dead-heading combined) and table 6.4 shows an average time of all current simulation runs of 4,13 minutes. The difference is likely caused by the fact that currently the forklifts receive tasks from the foreman and these tasks consist of a number of SKUs of the same type that have to be delivered. In the simulation, the forklift will receive tasks based on his location, reducing the amount of time spend dead-heading.

The difference between the reality and the simulation can also be caused by the fact that in reality forklifts will not always move at 5 km/h, as they have to slow down in corners or under heavy loads. Furthermore the forklifts will not always use the shortest path to reach their destination due to the fact that operators can decide on the route themselves and some aisles may be obstructed.

Policy	Total Working time [min]	Working time per SKU [min]
Zones	4.853	3,34
Near Destination	6.204	4,26
Near Origin	6.970	4,79
Average	**6.009**	**4,13**

Table 6.4. Working times per policy with 1.455 SKUs per day

6.2.4 Conclusion

Following the reasons and information provided above, it can be concluded that the simulation model may have the required accuracy, however, as there is no data to be found on a unit-load warehouse using an advanced WMS it is not possible to have a definitive answer to the question *'Is it the right model?'*. Validation is made increasingly difficult due to the stochastically defined input of the model.

Chapter 7

Experiments

7.1 Experimental plan

To be able to answer the research question as defined in chapter 4, two case studies will be performed based on the warehouse of Nijman/Zeetank in Chmielów. The first case study will use the current throughput and will vary the number of forklifts from 14 to 3 for all three storage policies. The second case study will use the predicted growth of the throughput and will vary the number of forklifts based on the results of the first case.

The input for these cases will have the same number of initial SKUs in the same composition of Raw, WIP and finished product. For each storage policy a different storage location is chosen for each SKU, but kept the same for all simulation runs. Furthermore, the number of shipments is equal for each run in a case, as these are scheduled and the schedule is known in advance.

The variation in the simulations comes from the distributions in the production lines and the inbound batches, as there is no schedule for this supply.

7.1.1 Runtime

For the simulation a net number of operational hours per day was set to 22 hours, as Nijman/Zeetank operates a three-shift around the clock operation. Each shift change takes around 10 minutes, as operators stop 5 minutes before the end of shift and the next shift has a quick meeting of 5 minutes before starting. Also each shift has a 15 minute break and the batteries of the forklift should be changed twice a day, taking about 15 to 20 minutes per change. This leaves a net operational time of 22 hours or 1320 minutes (table 7.1).

What	Repetitions	Time
One day	1	24 hours
Breaks	3	15 minutes
Battery change	2	15-20 minutes
Shift change	3	10 minutes
Total		**22 hours**
		(1320 minutes)

Table 7.1. Net operational hours per day

To determine the runtime of the simulations, a simulation of 1 week (9.240 minutes) was completed to find the length of the initial peak. This was done with the Zones storage policy and 14 forklifts and the results are shown in figure 7.1. The figure shows a peak right at the start that drops below 40% almost immediately, from the data it appears that this happens after 95 minutes of simulation and the percentage of worked time drops below 30% after 302 minutes. Furthermore the amount of worked time starts to increase again after 5000 minutes to a level that is close to the average amount of worked time at 1000 minutes.

Figures 7.2, 7.3 and 7.4 shows the amount of tasks released into the warehouse that are not yet completed, which gives an indication of the amount of work that is still to be done. In this graph it can be seen that each storage policy has a period of time that has no tasks in the system within the first three hours of the simulation and the startup tasks at the beginning of the simulation are completed. Taking into account the information gathered from figure 7.1, 7.2, 7.3 and 7.4, the runtime of the simulation is chosen to be one net operational day or 1320 minutes

7.1.2 Number of Runs

The number of runs was determined using section 24.4, *'Determining the sample size'*, of Dekking (2005) which gives the following equation:

$$n \geq \left(\frac{2 z_{\alpha/2} \sigma}{w} \right)^2 \tag{7.1}$$

In this equation n is the number of runs, $z_{\alpha/2}$ is the critical value, σ is the standard deviation and w is the width of the confidence interval.

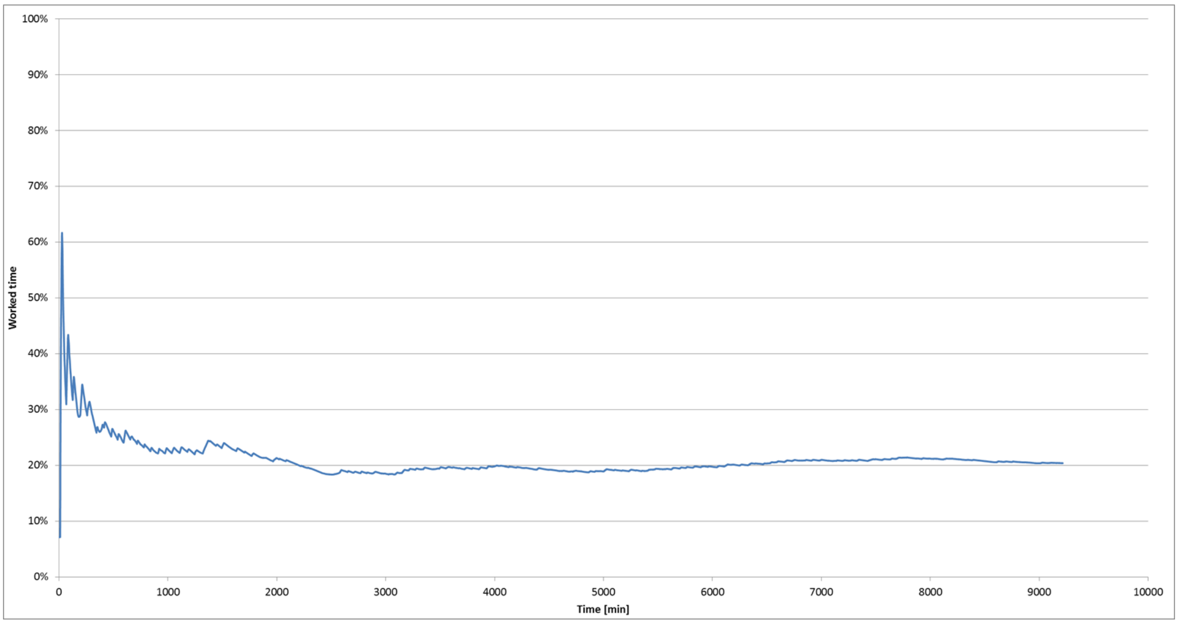

Figure 7.1. Worked time result of the week simulation

To calculate the number of runs, an assumption has been made about the standard deviation. To do this, the simulation with 14 forklifts operating under the storage policy of Near Destination, was run 25 times to provide a baseline. Table 7.2 shows the results of these simulation runs with the mean and standard deviation. Using the standard deviation σ of 2,21%, a confidence level α of 95% and a width w of 0,05, equation 7.1 becomes:

$$n \geq \left(\frac{2 \cdot 1,96 \cdot 0,0221}{0,005} \right)^2$$

$$n \geq 3,002$$

The number of runs should be more than 3,002 and to increase the accuracy of the mean, each variation of the system will be run for 5 times.

Run	1	2	3	4	5	6	7	8	9	10	11	12	
Worked time	36%	32%	35%	35%	30%	33%	36%	39%	37%	32%	35%	36%	
Run	13	14	15	16	17	18	19	20	21	22	23	24	25
Worked time	34%	34%	32%	33%	36%	35%	32%	36%	35%	35%	37%	32%	30%

Table 7.2. Results of the 25 runs for the Near Destination policy with 14 forklifts

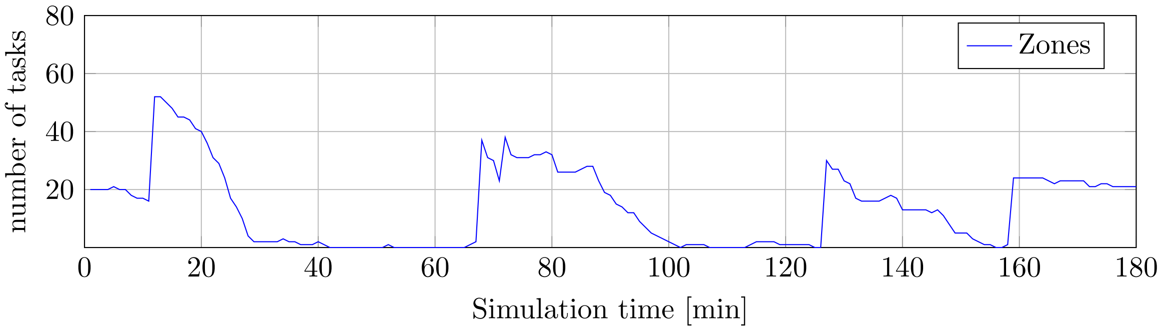

Figure 7.2. number of tasks in the simulation with the Zones storage policy and 7 forklifts

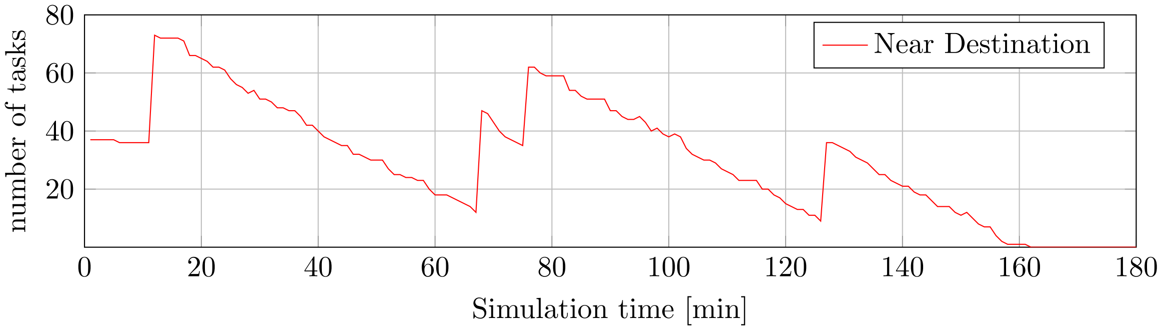

Figure 7.3. number of tasks in the simulation with the Near Destination storage policy and 8 forklifts

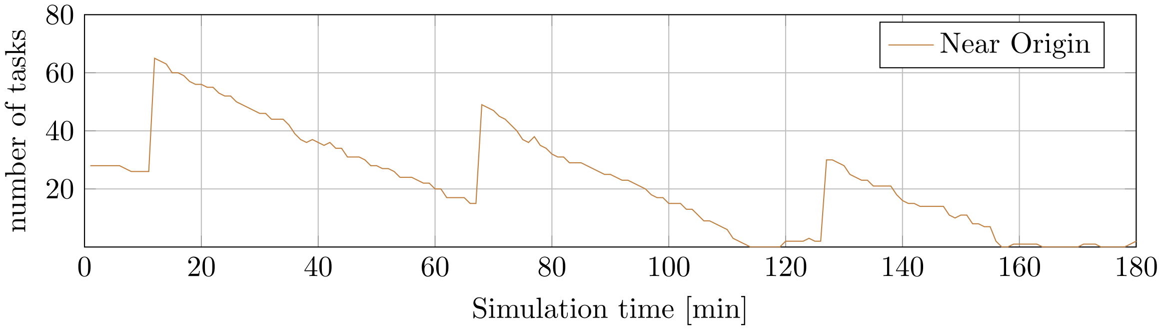

Figure 7.4. number of tasks in the simulation with the Near Origin storage policy and 8 forklifts

7.2 Case I: Nijman/Zeetank Chmielów: Current throughput

7.2.1 Input

This case uses the warehouse as described in chapter 2 and will vary the number of forklifts from 14 down to 3, for all three storage policies. Using the product flows shown in table 2.4 the supply and demand for all clients of the warehouse was determined and presented in table 7.3. These values were put in using table distributions that contain all the data for the supply and demand of the clients for the year 2015.

Client	Raw		WIP		Finished	
	To	From	To	From	To	From
Trucks		65	296	203	164	126
Production 1	45			84		23
Production 2A			76	124		21
Production 2B			114	73		24

Table 7.3. Supply and demand of Case I

7.2.2 Results

Figures 7.5 and 7.6 show the results of the simulation with the current throughput (the data is presented in appendix D.1). Figure 7.5 shows the lead time of the tasks for the different number of forklifts in the warehouse. It shows a clear point were the amount of work per forklift becomes so much that they are unable to process everything in time. For the Near Destination and Near Origin cases it is found that the warehouse is able to operate with 8 forklifts, and for the Zones policy with 7 forklifts, as these combinations of forklifts and storage policies have a lead time that resembles the minimum lead time, found in the simulations with 14 forklifts. Still the differences between the different policies are rather small. This changes when looking at figure 7.6, were the difference between the different policies is more evident. The difference in the policies is most likely caused by the location of the different clients, as the transfer zones are located closely to the corners of the warehouse, leading to increased distances between the storage bins and the clients, which in turn lead to longer driving times and therefore more worked time. When using the Zones storage policy this is not an issue as the deciding factor is the type of product and not its origin or destination.

Figure 7.7 shows the number of tasks in the warehouse during the course of a simulation run and a calculated day. It is visiblle that there are a number of periods where there are no tasks available and the forklifts stand idle. As the worked time percentage is 54%, the forklifts will be idle for almost half of the total operational time. When the average lead time is calculated for an evenly distributed day it is found to be 9,72 minutes, whereas figure 7.5 shows that for 7 forklifts in the Zones policy the lead time is 17,6 minutes. This difference is most likely caused by the fact that in the calculation the inbound trucks and the supply and demand of the production lines are evenly distributed, whereas in the simulation these are variable both in time and in amount, leading to higher peaks. When comparing the highest peaks, it appears that the simulation has a peak that is 1,5 times higher than that of the calculations (47 versus 73 tasks). Furthermore, as can be seen in table 7.4, this leads to a duration that is more than 2,3 times higher. During the peak in the simulation the forklifts completed 119 tasks and in the calculation 62 tasks were completed. The average time it took to complete a task is almost equal. However the lead time for the simulation is much higher, almost twice as high, which is caused by the larger number of tasks in the system.

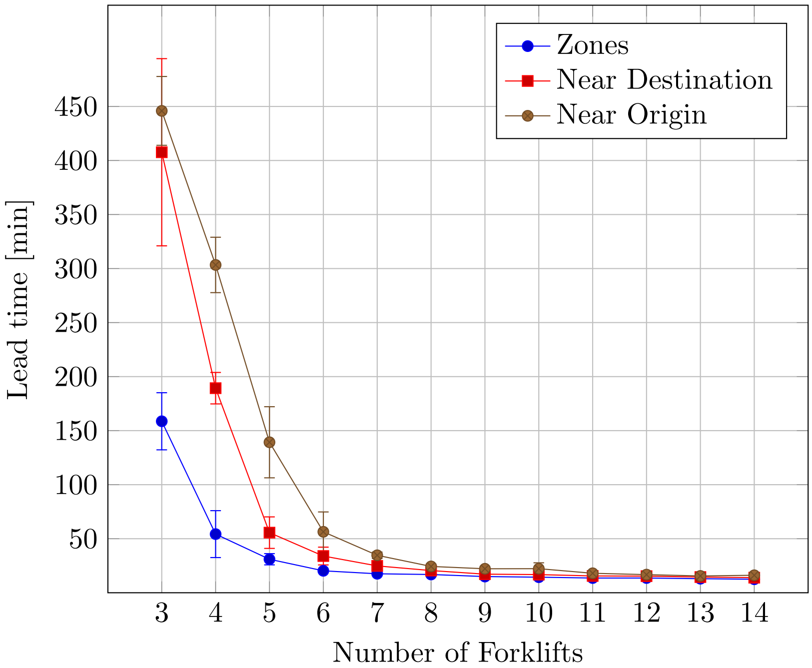

Figure 7.5. Lead time with the current throughput

	Calculation	Simulation
Peak duration [min]	32	74
Peak number of tasks	47	73
Tasks completed during peak	62	119
Worked time per task [min]	(table 6.4) 4,13	4,35
Lead time [min]	12,9	23,9

Table 7.4. Difference between the calculations and the simulations

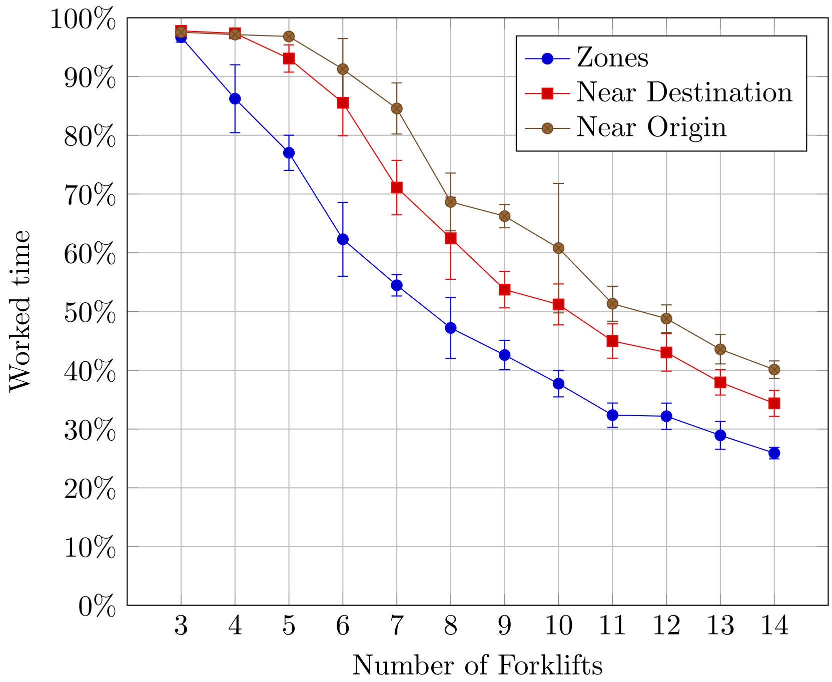

Figure 7.6. Worked time with the current throughput

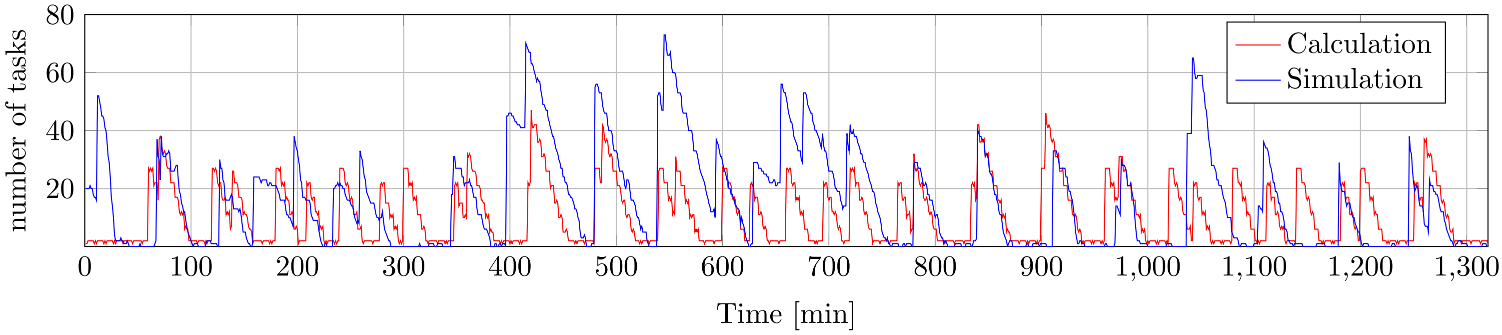

Figure 7.7. number of tasks over time

7.3 Case II: Nijman/Zeetank Chmielów: Future throughput

7.3.1 Input

As a result of the new production line being taken into use, the demand from NSG Pilkington will increase. As this new production lines is similar to one already producing automotive glass in another location, an accurate estimate can be made on the amount and composition of the throughput. The new production line will demand 108 SKU of raw glass and produce 180 SKU of finished products every day. The SKU with raw glass has to be delivered to the warehouse by trucks and the finished products will leave again in outbound shipments. This information lead to the supply and demand input presented in table 7.5.

Furthermore, as the results from section 7.2.2, and more specific figure 7.5, show that with the current throughput a minimum number of 7 forklifts is required to maintain a lead time that is comparable with the current possible lead time, the number of forklifts is varied from 6 up to 17.

	Raw		WIP		Finished	
Client	To	From	To	From	To	From
Trucks		169	296	203	335	126
Production 1	149			84		194
Production 2A			76	124		21
Production 2B			114	73		24

Table 7.5. Supply and demand of Case II

7.3.2 Results

The results of the second case are presented in figures 7.8 and 7.9 and the data for these graphs can be found in appendix D.2. Figure 7.8 shows a significant difference between the three different storage policies, because for the Near Origin storage policy a lead time of around 25 minutes is only reached with 17 forklifts, whereas for the Zones storage policy, this lead time is reached with only 12 forklift. This difference is larger than was observed in section 7.2.2 which is most likely caused by the increase in demand from Production 1, leading to more traffic in that area and more products stored in that location.

Figure 7.9 shows almost the same image as figure 7.6 but with a different number of forklifts. Again due to the location of the transfer zones the traffic in the corners of the warehouse and the amount of SKU in the warehouse, the driving times for the Near Destination and Near Origin storage policies is higher than that of the Zones policy.

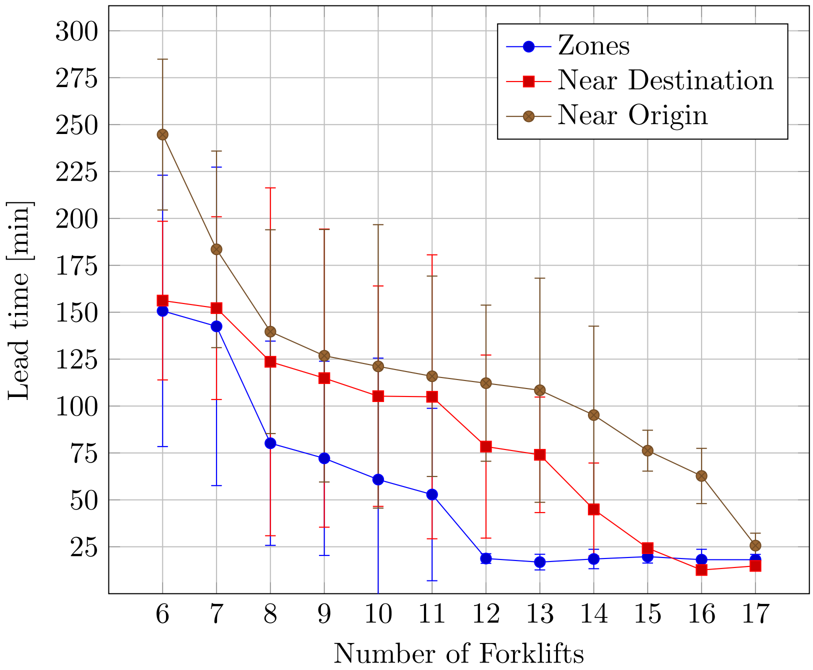

Figure 7.8. Lead time with the future throughput

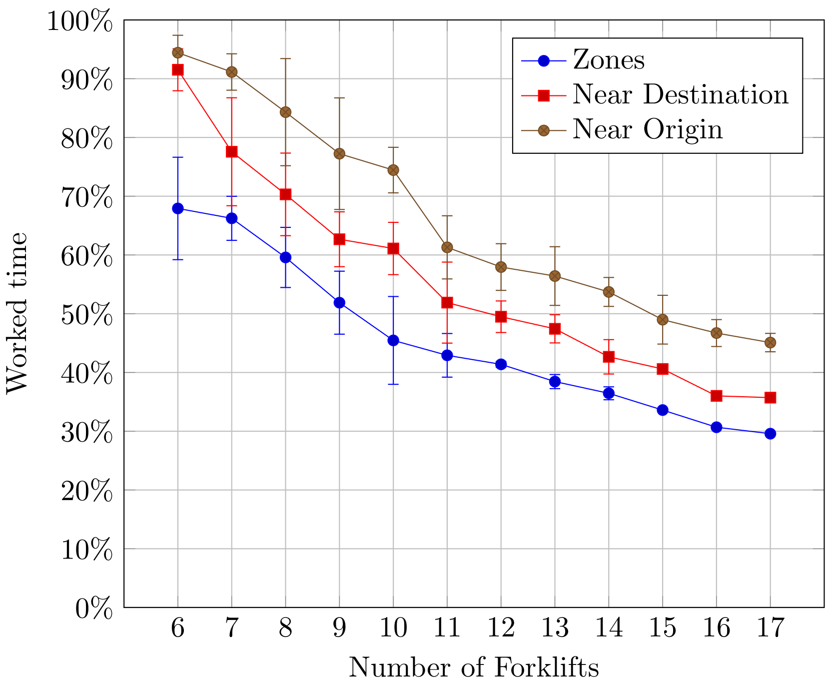

Figure 7.9. Worked time with the future throughput

Chapter 8

Conclusion

The main goal of this research was to help the warehouse manager of Nijman/Zeetank in making the decisions on a tactical level to improve the operational performance. Therefore the main research question is:

> How are the forklifts and storage area of Nijman/Zeetank in Chmielów to be used to meet the expected increase in demand from NSG Pilkington in an efficient and effective way?

Following the results of the experiments done during this research it was found that in the current situation the number of forklifts can be reduced from 14 to 8 for all three storage policies, and the operation will be able to run with only 7 forklifts when the current layout of the warehouse is kept in place. Thus when the new production line is started to its full potential the differences between the storage policies become more evident and it is found that it still is possible to reduce the number of forklifts to 12, again using the current zones, and only changing the way SKUs are stored in the zones, sorted on expected delivery time.

To formulate the main research question the following questions were answered and a summary is given:

1. **What is the current situation in the warehouse of Nijman/Zeetank in Poland and why should it be improved?**
   Nijman/Zeetank looks to improve their operations to be able to keep up with the growing production of NSG Pilkington, which is the largest incentive to improve the operations. At this moment almost 40% of the working time of the forklifts is used for the digging for the SKUs and waiting on aisles to clear, which is caused by a lack

of available real-time information during the storage proces. This lack of information leads to the forklift operators deciding on their own where to store the SKUs. To reduce or even eliminate the time spend digging and waiting for aisles to clear, the forklift operators need to recieve accurate storage tasks based on real-time information.

2. **What is warehousing?**
   Warehousing is the service to store SKU and deliver these to the clients at the requested time. Warehouses are used to bring products together to reduce transportation cost, achieve economies of scale in manufacturing or purchasing or provide value added processes and shorten response time.

3. **How can the operational performance be measured?**
   The operational performance can be measured using the performance indicators from section 3.1.2, the Key Performance Indicator (KPI) are defined as the task lead time and the utilisation rate of the forklifts.

4. **What are the decisions made on the different levels (Strategic, Tactical, Operational)?**
   On the strategic level the decisions are mostly concerned with answering the question *'What resources can I use?'*, as this is a long term decision and will decide if they continue to work with the current equipment or change the number and type of resources in the operation.

   For the tactical decisions the question asked is *'How do I use my resources?'*, as this will influence the day-to-day operations, and will create guidelines in how to handle the different parts of the process. A typical tactical decision is the choice of Storage Location Assignment policy.

   The operational decisions are concerned with the question *'What do I do when ... happens?'* These decisions are made during the day-to-day operations and involve the resource utilisation, the quality of service provided, the timely delivery of SKUs to the different output zones, and the various disturbances in the process.

5. **What kind of decision support system is most suited for the problem?**
   All state changes in the system are triggered by stochastically defined supply and demand, a discrete event simulation is developed to simulate the warehouse and calculate the operational performance.

8.1 Final advice

For the improvement of the operations in the warehouse in Chmielów there are a number of actions that can be performed in order to improve the processes.

1. Standardize the forklift fleet, as a large portion of the tasks are given in batches due to the arrival and departure of trucks, it is key to have as many resources capable of performing these task, in order to prevent build up that result in longer lead times and lower the customer service level. This will also reduce the amount of product stored in the aisles, as each forklift will deliver the picked SKU to its destination, instead of combining them in the aisle, and having a larger forklift drive them to their destination.

2. To reduce the amount of digging and searching for the SKUs it is possible to use the barcode scanners in combination with a put away strategy and implementation into the ERP of NSG Pilkington. The scanners can be used to give a put away advice to speed up the process and reduce the eventual picking time. This, however, will not eliminate the searching and digging.

3. Implement an advanced WMS with locating capabilities. This will reduce, if not eliminate, the digging time and will certainly eliminate the time spend flagging the SKUs, as there is no more need to search for a SKU.

4. When SKU are staged, customer labels must be attached and as proof a picture must be taken, this is a time consuming activity and can be reduced by installing a label printer on each forklift that automatically prints the customer label that the forklift operator can attach.

For all actions mentioned above it is recommended to first make a stakeholder analysis, as this was not a part of the research. Furthermore a design for the change process should be made as this will require a well defined and scheduled plan.

8.2 Recommendations

Simulation model

The simulation model could be extended with more exceptions and more detailed information regarding the different types of products, containers, certain forklifts that are unable to move certain SKU. These extensions will increase the accuracy of the model but the results will stay in the same order of magnitude. Furthermore it is recommended that after Nijman/Zeetank decides to implement an advanced WMS, the simulation model is validated against the future performance. This will lead to a larger credibility for future research using this simulation model.

Another improvement that could be made in the simulation model is the improvement of the task assignment. Now when a task is assigned only the current available forklifts are taken into account, but the operations might become more efficient when the forklifts that are almost finished are also taken into account. The task assignment will look at the forklifts that are about to finish their tasks and will assign them tasks near the destination of their current task.

Change process

Before the implementation of the advanced WMS, a design for the change process should be made in order to limit the inconvenience for the clients, as they still expect the same service level but there will be a large amount of extra handling.

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Appendices

Simulation model for warehouse operation improvement through advanced WMS/Locating systems

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Abstract

Nijman/Zeetank International Logistic Group is responsible for the reception, storage and delivery of containers of automotive glass in Chmielów and is expecting an increase in the demand from the owner of the production facility, NSG Pilkington. To cope with this expected increase, Nijman/Zeetank looks to improve their warehousing operations by implementing an advanced Warehouse Management System with locating capabilities. To assist the warehouse manager in making his decisions regarding the utilisation of the available resources the objective of this research is to develop a decision support system. The decisions support system that is developed is a simulation model which is capable of simulating the warehouse on an operational level. Using the simulation model, the warehouse of Nijman/Zeetank is simulated with both the current and the expected future throughput. According to the conducted experiments, the conclusion can be drawn that with the current throughput the number of forklifts can be reduced from 14 to 7, and for the expected increase in demand the required number of forklifts is 12. With the implementation of the advanced WMS, Nijman/Zeetank is able to improve their operation and save on the number of forklifts in the warehouse.

I. Introduction

Nijman/Zeetank International Logistic Group is a logistics service provider that specializes in the transport of glass, petrochemicals, fuels, gasses and general cargo and also offers services for warehousing, handling and storage of containers, heating facilities, weigh bridge, drum filling and custom clearance activities. One of their operations is the internal logistics in a production plant for automotive glass of NSG Pilkington, one of the world's leading producers of glass.

The responsibility of Nijman/Zeetank starts with the reception of raw glass, semi-finished and finished products from either inbound trucks or from the production lines. After receiving these products they are transferred to the warehouse and stored awaiting reprocessing or shipping to the customer. To be able to keep up with the rising demand for efficiency, cost reduction, and the forecast of increased production coming from NSG Pilkington, Nijman/Zeetank looks to improve their warehouse operations by implementing an advanced Warehouse Management System (WMS) with locating capabilities.

To help the warehouse manager in his decisions regarding the utilisation of the available resources a decision support system is to be developed that will answer the main research question: *'How are the forklifts and storage area of Nijman/Zeetank in Chmielów to be used to meet the expected increase in demand from NSG Pilkington in an efficient and effective way?'*.

II. Current situation

According to Gu, Goetschalckx, and McGinnis (2007) warehouse operations are divided in four main categories: Receiving, Storage, Order picking and Shipping. However Bartholdi III and Hackman (2011) and De Koster, Le-Duc, and Roodbergen (2007) added a fifth category, Accumulation/sortation, between Order picking and Shipping. Both receiving and shipping are the interface of a warehouse for incoming and outgoing material flow. Incoming shipments are brought to the warehouse, unloaded at the receiving docks, and put into storage. For the shipping the orders are picked from storage, prepared, and shipped to the customers through the shipping docks. When a product is moved directly from receiving to shipping, the process involved is called Cross-docking.

Nijman/Zeetank has the role of a Third Party Logistics (3PL) provider and is responsible for all logistical operations in the production plant and delivers all warehousing services to NSG Pilkington in Chmielów. They receive product orders from NSG Pilkington and have to report back when orders are completed. Furthermore, Nijman/Zeetank is responsible for the transportation of Stock Keeping Units (SKUs) with glass between the production plant in Sandomierz and Chmielów, a distance of just 25 km.

Nijman/Zeetank is operating as a reactive player in the supply chain, which means that they are completely in the dark about the organisation of NSG Pilkington. Besides, decisions about the amount of product produced is only communicated at the moment it arrives. Nijman/Zeetank has no other choice but to react to the amount of product moving in and decisions made by other departments.

At this moment Nijman/Zeetank moves an average of 1.455 SKUs through the warehouse every day and these SKUs stay in the warehouse for an average of 10,6 days. These SKUs are moved by 14 forklifts of various sizes, from which their time is divided in five different activities, the moving of the SKU, including pick up and put away, dead-heading or driving empty, digging, waiting for aisles to clear, and searching for the SKUs to ship, also called flagging. At Nijman/Zeetank the most time is spend digging, as stock is now stored in a block stack and must be retrieved according to First-In,First-Out.

Each part of the warehouse operations in Chmielów has the potential for improvement as each part copes with a lack of information available and Nijman/Zeetank looks to improve their operations to be able to cope with the expected increase in demand from NSG Pilkington.

III. Analysis

A warehouse is a facility in the supply chain that brings products together to reduce transportation cost, achieve economies of scale in manufacturing or in purchasing or provide value added processes and shorten response time (Subramanya, Rangaswamy, et al., 2012).

i. Generalisation

Figure 1 shows the PROPER model (Veeke, Ottjes, & Lodewijks, 2008) of the warehouse of Nijman/Zeetank and shows how the three main flows are defined. The order flow is defined as the trucks and the production lines, as they create the tasks for the movement of SKUs. The product flow contains all SKUs that are moved through the warehouse and the resources are the forklifts and the storage area.

ii. Decision making

Decisions are made on all levels of an operation, from the managers on the top, who decide what the company should aim for in the future, to the operators on the floor, who decide on how to do the next step of the operation for the job at hand. If it is translated to a warehouse where to store a SKU. These decisions can be categorized in three different levels: Strategic, Tactical and Operational.

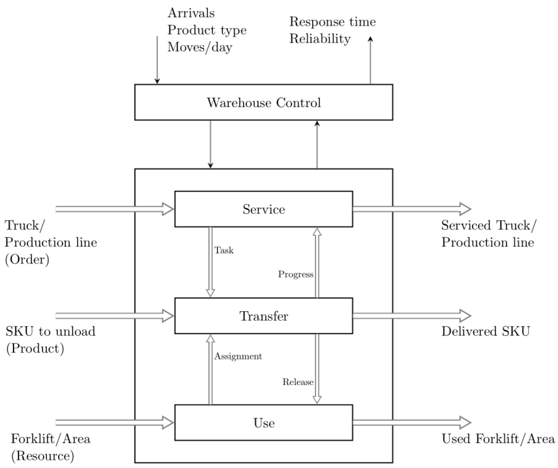

Figure 1. *PROPER model of the warehouse of Nijman/Zeetank*

The Strategic decisions in a warehouse aim to answer the question *'What resources can I use?'* With this in mind objectives can be set for the operation, such as creating long-term projections for the future, missions statements, overall corporate objectives, strategic business unit objectives, and tactical objectives (Boundless, 2015).

Tactical decisions are made by all levels of management in an operation and involve changes in the processes of the operation. Here the existing process and its management is reviewed and changed to eliminate nonvalue-adding procedures and to balance the different flows. By using creative solutions at this level it is possible to shift the flow or the capacity of the existing systems with minimal capital investment (McNair, Vangermeersch, et al., 1998). On a tactical level the decision try to answer the question *'How do I use my resources?'*, as this will influence the day-to-day operations of the warehouse, and will create guidelines in how to handle the different parts of the process.

The operational decisions are made for the short term and are aimed at their impact on current profits and costs. Due to their short term horizon and focus on the day-to-day operations, these decisions are often taken repetitively and answer the question *'What do I do when ... happens?'*.

iii. Storage location assignment policies

With the WMS the amount of real time information in the warehouse is increased and it is possible to track each individual SKU. This gives the opportunity to change the storage policies in the warehouse. For this research three different storage policies were tested, starting with keeping the current zones in the warehouse in place. The second policy tries to store the SKUs as close to their destination as possible and the third close to the point of entry in the warehouse. For all three policies the placement in a storage bin is no longer based on the type of product but more so on the time it needs to be delivered to the customer. Therefore it is possible that multiple product types are placed in a single storage bin.

IV. Model

Due to the fact that all input values are stochastically defined, a discrete event simulation is developed as the decision support tool. The model will simulate the warehouse with the supply and demand of the clients and will do this at an operational level, simulating all movements of the forklifts.

The Key Performance Indicators were defined to firstly be the Task lead time, as the warehouse provides a service and customers expect a fast delivery, and secondly the utilisation of the forklifts, as this shows if they are used in an effective and efficient way.

To calculate the Task lead time each SKU has a final delivery time before which the task must be executed. To do this, the tasks are released into the system one hour before the delivery time. This time is recorded as the release time $T_{release}$. When the task is completed it is stored with its release time and the completion time $T_{complete}$. Equation 1 shows how these times are used to calculate the Task lead times.

$$T_{lead} = T_{complete} - T_{release} \tag{1}$$

The forklift utilisation is found by recording the times spend by the forklifts during the different activities. These times are stored with the current simulation time T_{now} and the time spend on that activity. The different activities are: driving empty, driving loaded, picking an SKU, and putting an SKU down. Furthermore the total working time is recorded. Equation 2 shows how the working time T_{work} is used to calculate the worked time percentage, and further includes the total time simulated T_{Total} and the number of forklifts $n_{forklift}$.

$$Worked\ time = \frac{T_{work}}{T_{Total} \cdot n_{forklift}} \cdot 100\% \quad (2)$$

V. Experiments

The experiments consist of two cases, one using the warehouse of Nijman/Zeetank with the current throughput and one with the expected increase in demand. These cases use the same initial stock which is distributed over the warehouse based on the used storage policy. For the case with the current throughput the number of forklifts is varied from the current number of forklifts, 14, down to 3 to find a clear overview of the required number of forklifts. For the future throughput this was done starting at 6 forklifts and increasing until 17 forklifts are used.

Figure 2 shows the resulting average lead time for the first case and it shows a clear point were the amount of work per forklift becomes so much that they are unable to process everything in time. For the Near Destination and Near Origin policies it is evident that 8 forklifts is the least amount required to maintain the lead time, and for the Zones policy this point is found at 7 forklifts. Therefore in terms of lead time the policies are not that different. However, when looking at figure 3 the difference become clearer, as the ratio of worked time is higher for the Near Destination and Near Origin policies.

The future throughput shows a much larger difference between the policies, Near Origin reaches a lead time of 25 minutes with 17 forklifts, whereas the Zones policy does that with 12 forklifts, as can be seen in figure 4. Figure 5 shows nearly the same trend as in the case with the current throughput, again the Near Origin policy has the highest ratio of worked time and the Zones policy the lowest. The difference between the policies is most likely caused by the location of the different clients, as the transfer zones are located closely to the corners of the warehouse. This leads to increased distances between the storage bins and the clients, which in turn lead to longer driving times and therefore more worked time. When using the Zones storage policy this is not an issue as the deciding factor is the type of product and not its origin or destination.

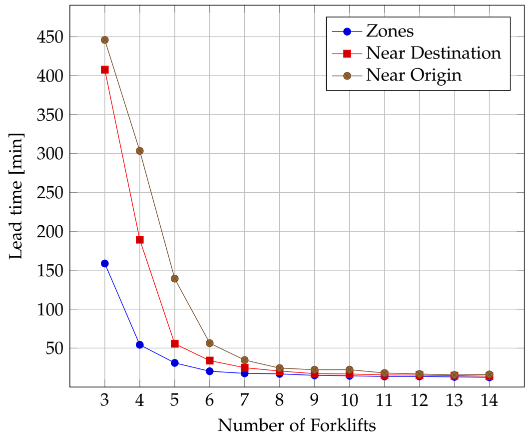

Figure 2. *Lead time with the current throughput*

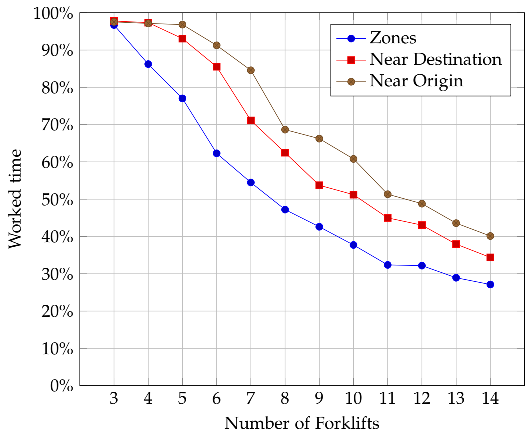

Figure 3. *Worked time with the current throughput*

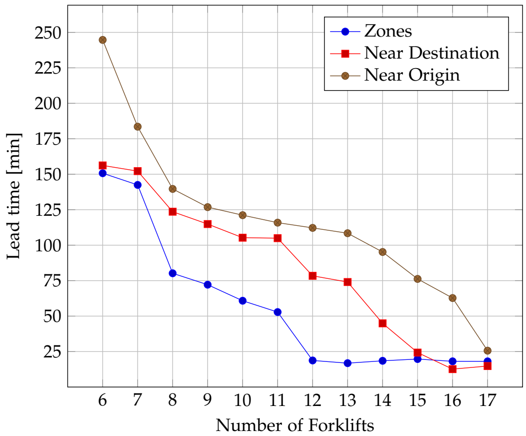

Figure 4. *Lead time with the future throughput*

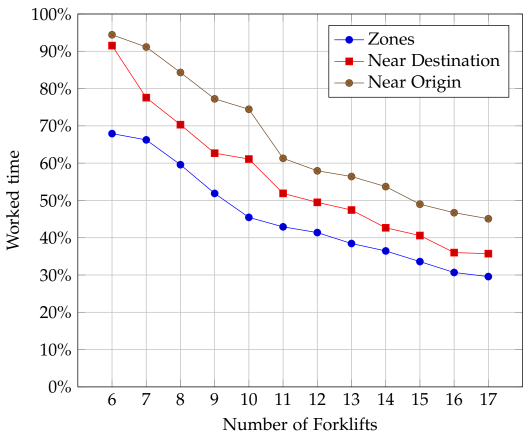

Figure 5. *Worked time with the future throughput*

VI. Conclusion

The goal of this research is to develop a decision support tool that id able to assist the warehouse manager in making the decisions on a tactical level to improve the operational performance. This model had to be able to help answer the main research question: *'How are the forklifts and storage area of Nijman/Zeetank in Chmielów to be used to meet the expected increase in demand from NSG Pilkington in an efficient and effective way?'*

Following the results of the experiments it can be concluded that in the current situation the number of forklifts can be reduced from 14 to 8 for all three storage policies, and even to 7 when the current layout of the warehouse is kept in place. For the future situation the amount of required forklifts can be reduced from the current 14 to 12, again using the Zones storage policy. Therefore it can be concluded that the implementation of an advanced Warehouse Management System with locating capabilities will lead to savings in terms of forklift working times and the required number of forklifts.

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Appendix B

Product handling procedures

B.1 Inbound from the unloading dock

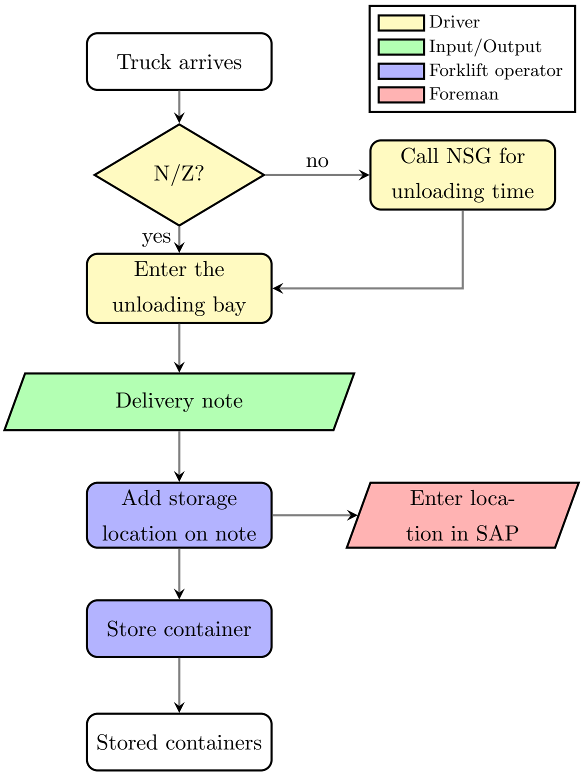

Figure B.1. Process for OE and AGR containers unloaded from inbound shipments

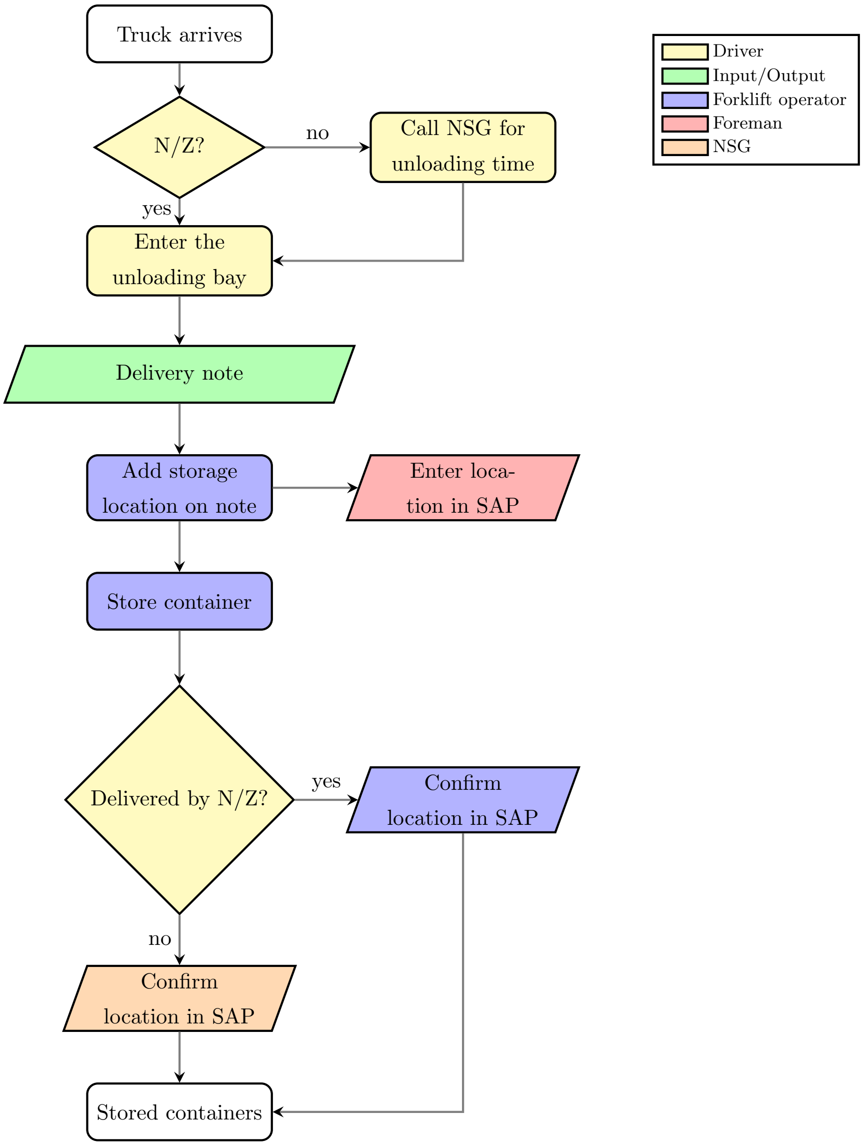

Figure B.2. Process for the WIP containers unloaded from the incoming shipments

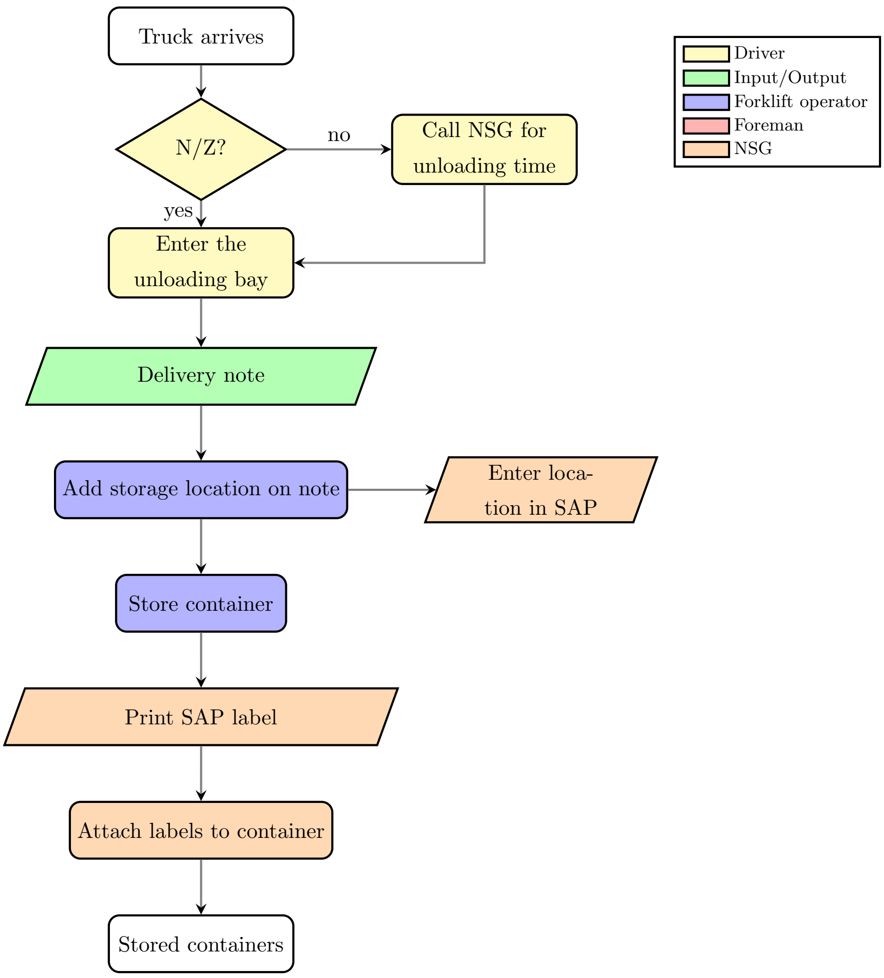

Figure B.3. Process for incoming Raw material

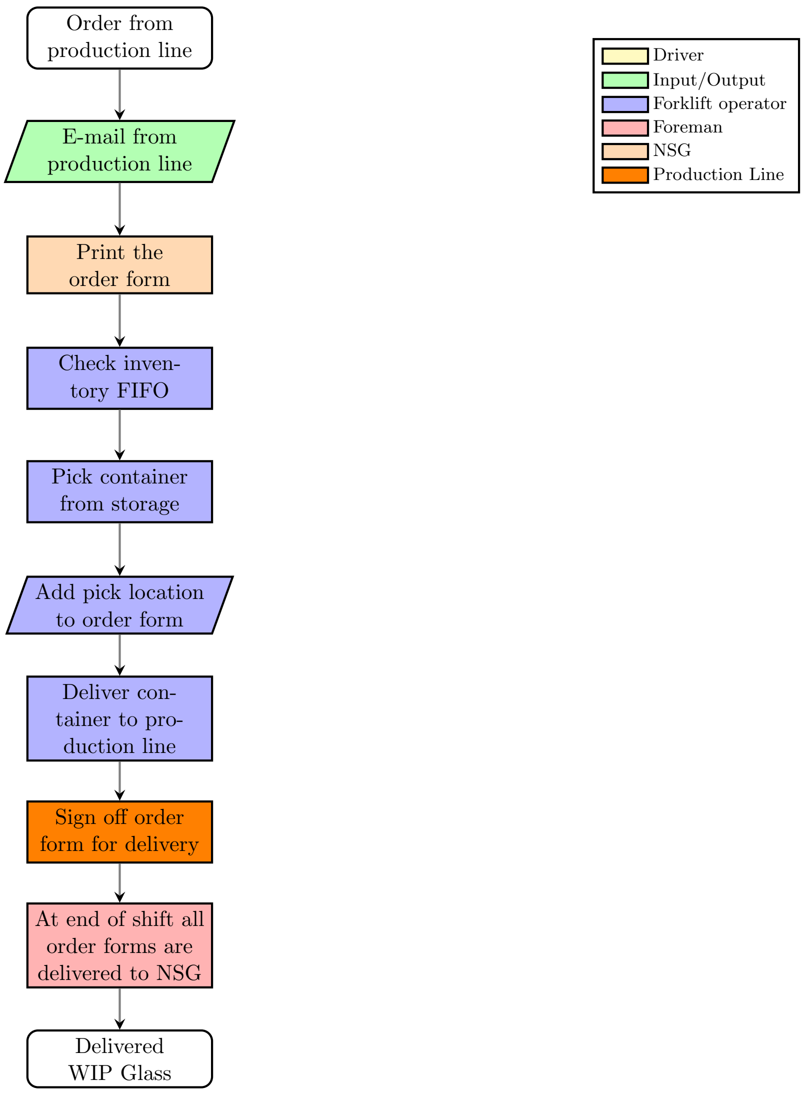

Figure B.4. Process for the transport of WIP to the production line

B.2 Outbound to production

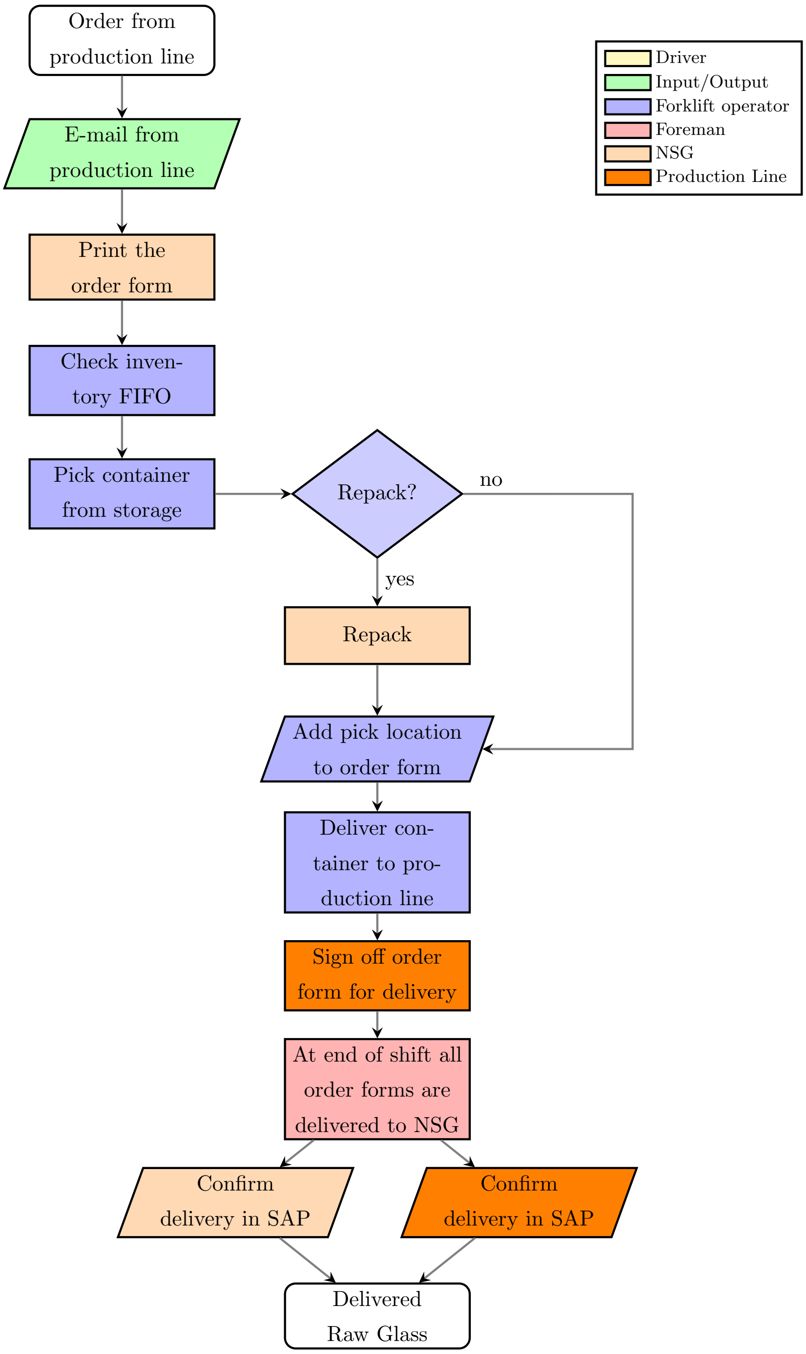

Figure B.5. Process for raw material moving to the production lines

B.3 Inbound from production

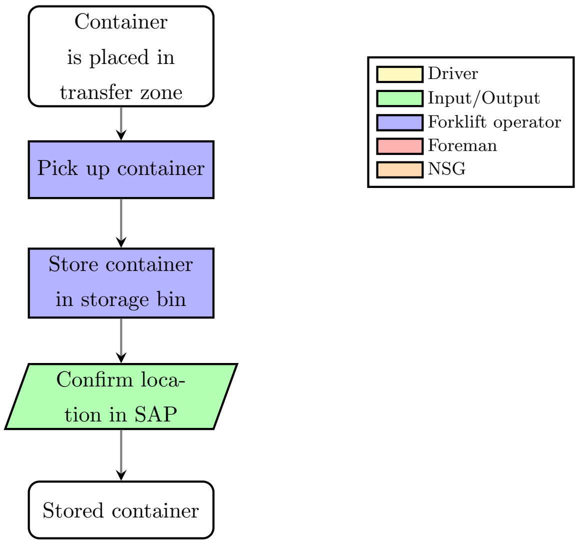

Figure B.6. Process for the OE and AGR from the production line

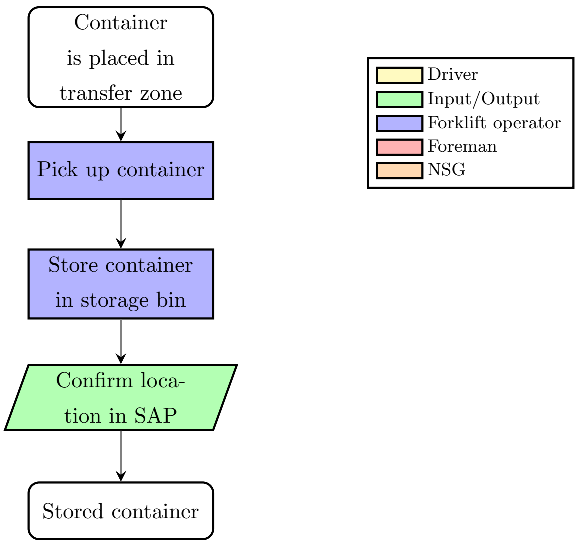

Figure B.7. Process for WIP containers inbound from the production lines

B.4 Outbound shipments

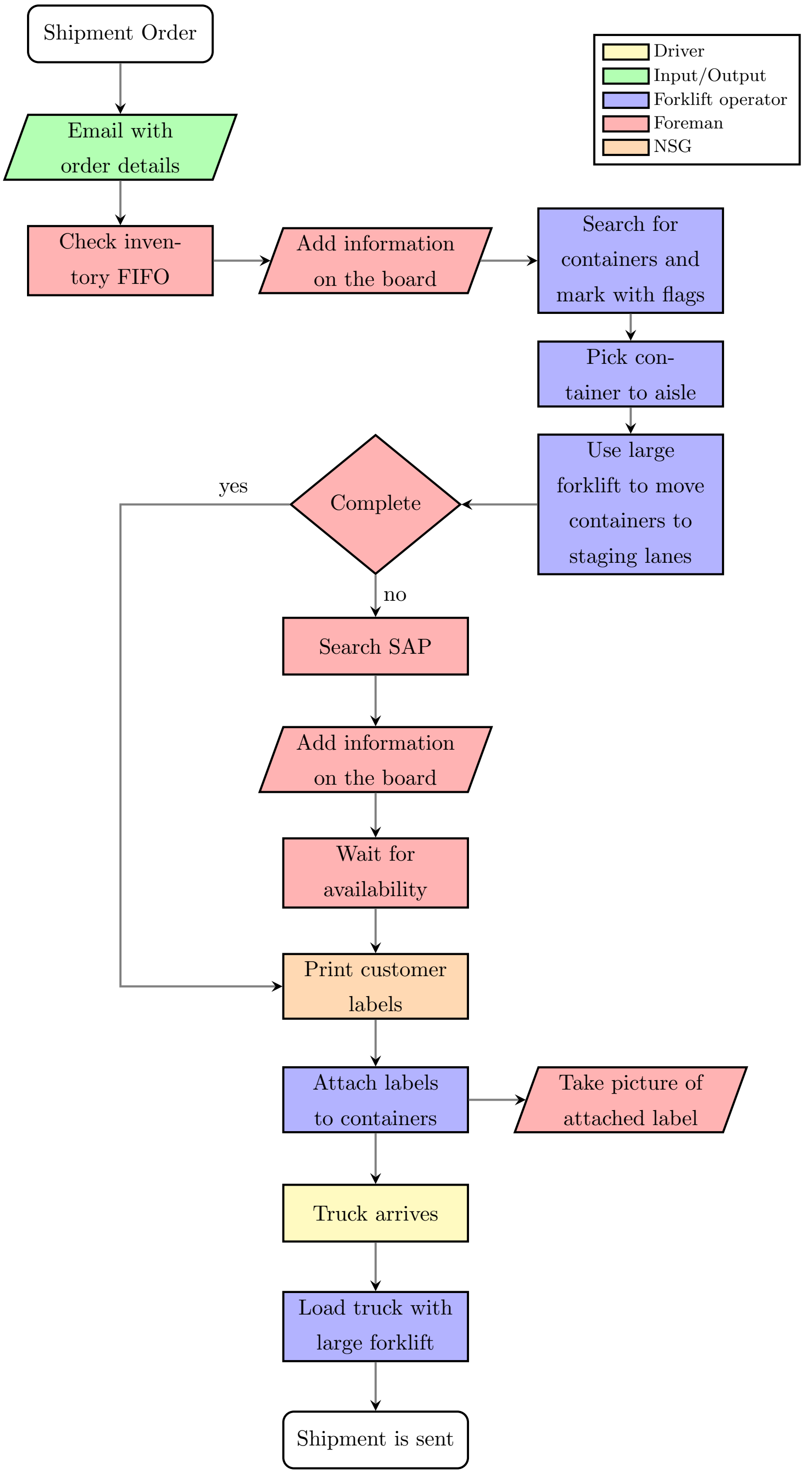

Figure B.8. Outbound flow of OE and AGR containers

Appendix C

Verification

C.1 Event trace

C.1.1 To TF1

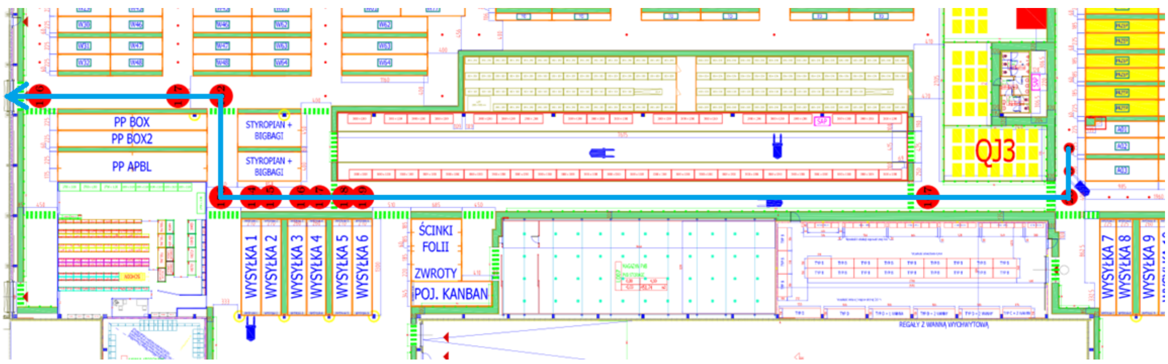

Figure C.1. Route to TF1

Node	X	Y	Distance to drive [m]	Driving time [min]	Total time [min]
2	146,3	28	3,1	0,037	
3	146,3	24,9	3,5	0,042	
23	146,3	21,4	18,9	0,227	
167	127,4	21,4	75,6	0,907	
159	51,8	21,4	2,4	0,029	
158	49,4	21,4	3,7	0,044	
157	45,7	21,4	2,5	0,030	
156	43,2	21,4	3,7	0,044	
155	39,5	21,4	2,5	0,030	
154	37	21,4	4,1	0,049	
153	32,9	21,4	13,6	0,163	
152	32,9	35	5,7	0,068	
147	27,2	35	18,5	0,222	
146	8,7	35	3,7	0,044	
TF1	5	34,98	3,7		1,94

Table C.1. Route to TF1

C.1.2 TF1 to W01

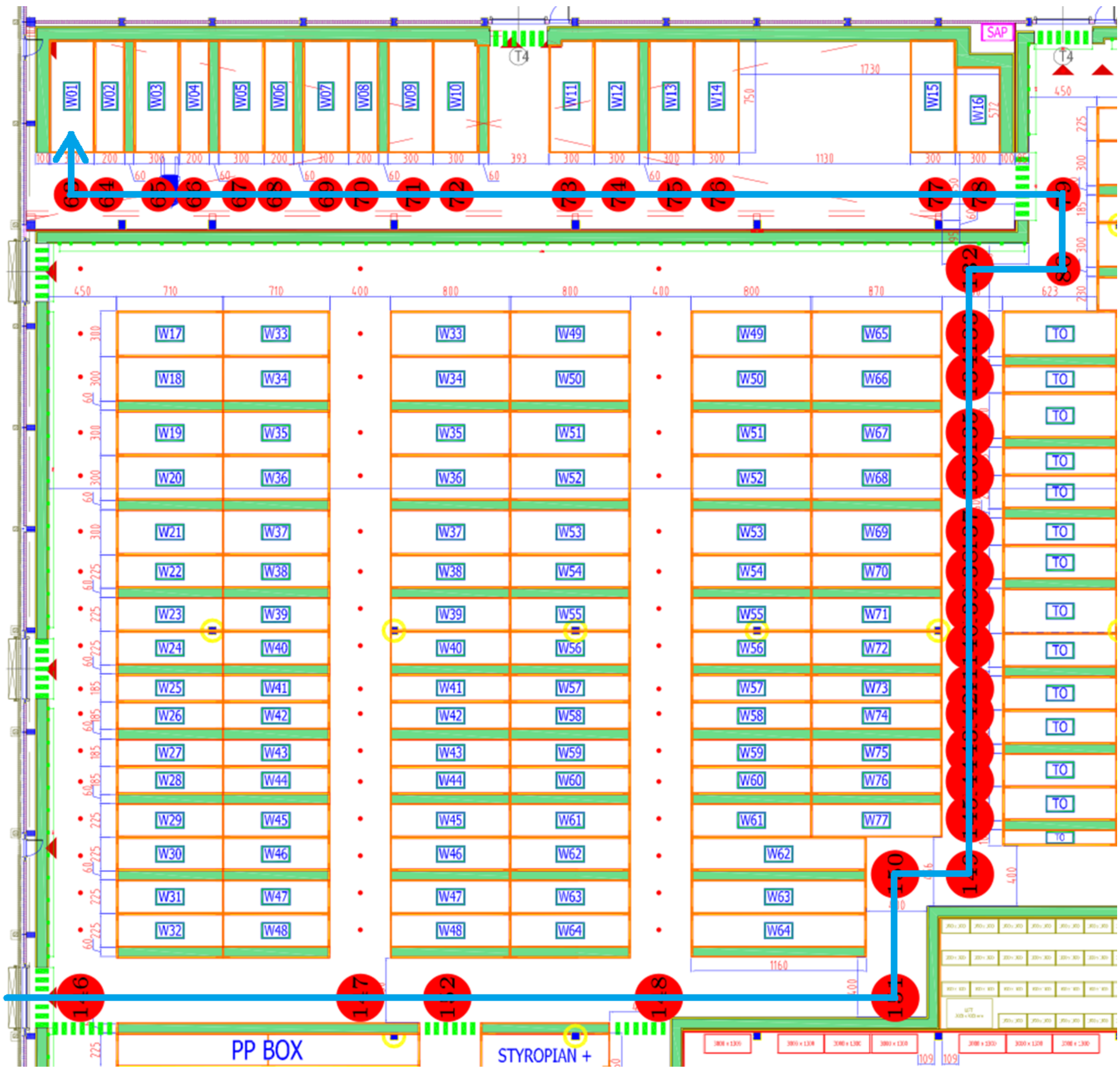

Figure C.2. Route from TF1 to W01

Node	X	Y	Distance to drive [m]	Driving time [min]	Total time [min]
TF1	5	34,98	3,7	0,044	1,94
146	8,7	35	18,5	0,222	
147	27,2	35	5,7	0,068	
152	32,9	35	14	0,168	
148	46,9	35	15,6	0,187	
151	62,5	35	8,2	0,098	
150	62,5	43,2	4,9	0,059	
149	67,4	43,2	3,7	0,044	
145	67,4	46,9	2,5	0,030	
144	67,4	49,4	2	0,024	
143	67,4	51,4	2,5	0,030	
142	67,4	53,9	1,6	0,019	
141	67,4	55,5	2,9	0,035	
140	67,4	58,4	2,5	0,030	
139	67,4	60,9	2,4	0,029	
138	67,4	63,3	2,7	0,032	
137	67,4	66	3,7	0,044	
136	67,4	69,7	2,9	0,035	
135	67,4	72,6	3,7	0,044	
134	67,4	76,3	2,8	0,034	
133	67,4	79,1	4,3	0,052	
132	67,4	83,4	6,2	0,074	
80	73,6	83,4	5	0,060	
79	73,6	88,4	5,6	0,067	
78	68	88,4	2,8	0,034	
77	65,2	88,4	14,4	0,173	
76	50,8	88,4	2,9	0,035	
75	47,9	88,4	3,7	0,044	
74	44,2	88,4	3,3	0,040	
73	40,9	88,4	7,4	0,089	
72	33,5	88,4	2,8	0,034	
71	30,7	88,4	3,4	0,041	
70	27,3	88,4	2,4	0,029	
69	24,9	88,4	3,4	0,041	
68	21,5	88,4	2,3	0,028	
67	19,2	88,4	3	0,036	
66	16,2	88,4	2,4	0,029	
65	13,8	88,4	3,4	0,041	
64	10,4	88,4	2,3	0,028	
63	8,1	88,4	3,196	0,038	
W01	6,64	91,24	3,196		4,22

Table C.2. Route from TF1 to W01

C.1.3 W01 to TF6

Figure C.3. Route from W01 to TF6, rotated 90 degrees

Node	X	Y	Distance to drive [m]	Driving time [min]	Total time [min]
W01	6,64	91,24	3,196	0,038	4,22
63	8,1	88,4	2,3	0,028	
64	10,4	88,4	3,4	0,041	
65	13,8	88,4	2,4	0,029	
66	16,2	88,4	3	0,036	
67	19,2	88,4	2,3	0,028	
68	21,5	88,4	3,4	0,041	
69	24,9	88,4	2,4	0,029	
70	27,3	88,4	3,4	0,041	
71	30,7	88,4	2,8	0,034	
72	33,5	88,4	7,4	0,089	
73	40,9	88,4	3,3	0,040	
74	44,2	88,4	3,7	0,044	
75	47,9	88,4	2,9	0,035	
76	50,8	88,4	14,4	0,173	
77	65,2	88,4	2,8	0,034	
78	68	88,4	5,6	0,067	
79	73,6	88,4	8,2	0,098	
160	73,6	96,6	13,5	0,162	
41	87,1	96,6	16,5	0,198	
171	103,6	96,6	3,3	0,040	
47	106,9	96,6	20,5	0,246	
53	127,4	96,6	18,9	0,227	
161	146,3	96,6	11,1	0,133	
162	157,4	96,6	12,7	0,152	
163	170,1	96,6	13,2	0,158	
164	170,1	83,4	23,4	0,281	
165	193,5	83,4	21,3	0,256	
166	193,5	62,1	7,4	0,089	
172	200,9	62,1	4,5	0,054	
178	200,9	66,6	2,5	0,030	
177	200,9	69,1	2,9	0,035	
176	200,9	72	1,8	0,022	
175	200,9	73,8	2,3	0,028	
174	200,9	76,1	2,1	0,025	
173	200,9	78,2	4	0,048	
287	200,9	82,2	11,9	0,143	
288	212,8	82,2	27,5	0,330	
289	212,8	109,7	5,3	0,064	
297	218,1	109,7	3,7	0,045	
TF6	218,15	113,42	3,7		7,95

Table C.3. Route from W01 to TF6

C.1.4 TF6 to A01

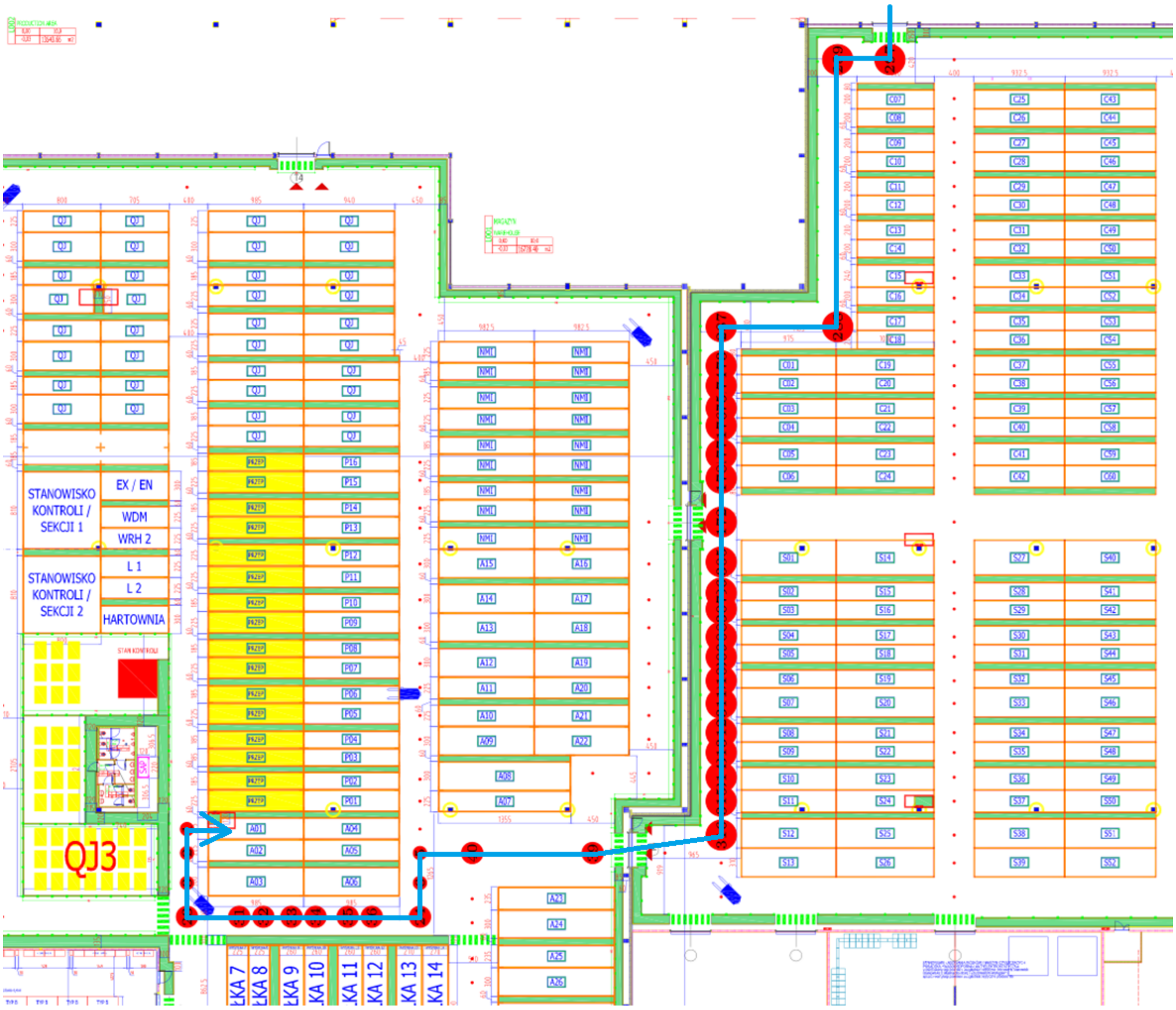

Figure C.4. Route from TF6 to A01

Node	X	Y	Distance to drive [m]	Driving time [min]	Total time [min]
TF6	218,15	113,42	3,7	0,045	7,95
297	218,1	109,7	5,3	0,064	
289	212,8	109,7	27,5	0,330	
288	212,8	82,2	11,9	0,143	
287	200,9	82,2	4	0,048	
173	200,9	78,2	2,1	0,025	
174	200,9	76,1	2,3	0,028	
175	200,9	73,8	1,8	0,022	
176	200,9	72	2,9	0,035	
177	200,9	69,1	2,5	0,030	
178	200,9	66,6	4,5	0,054	
172	200,9	62,1	4,1	0,049	
305	200,9	58	3,2	0,038	
306	200,9	54,8	1,7	0,020	
307	200,9	53,1	2,8	0,034	
308	200,9	50,3	2,1	0,025	
309	200,9	48,2	2,5	0,030	
310	200,9	45,7	2,3	0,028	
311	200,9	43,4	3	0,036	
312	200,9	40,4	2,1	0,025	
313	200,9	38,3	2,5	0,030	
314	200,9	35,8	2,5	0,030	
315	200,9	33,3	3,5	0,042	
316	200,9	29,8	13,2	0,160	
39	187,8	28	12,4	0,149	
40	175,4	28	5,3	0,064	
5	170,1	28	3,1	0,037	
6	170,1	24,9	3,5	0,042	
24	170,1	21,4	4,9	0,059	
36	165,2	21,4	2,5	0,030	
35	162,7	21,4	3,3	0,040	
34	159,4	21,4	1,6	0,019	
33	157,8	21,4	3,7	0,044	
32	154,1	21,4	2,5	0,030	
31	151,6	21,4	5,3	0,064	
23	146,3	21,4	3,5	0,042	
3	146,3	24,9	3,1	0,037	
2	146,3	28	2,5	0,030	
1	146,3	30,5	2,4	0,028	
A01	148,3	31,7	2,4		9,99

Table C.4. Route from TF6 to A01

C.1.5 A01 to TF4

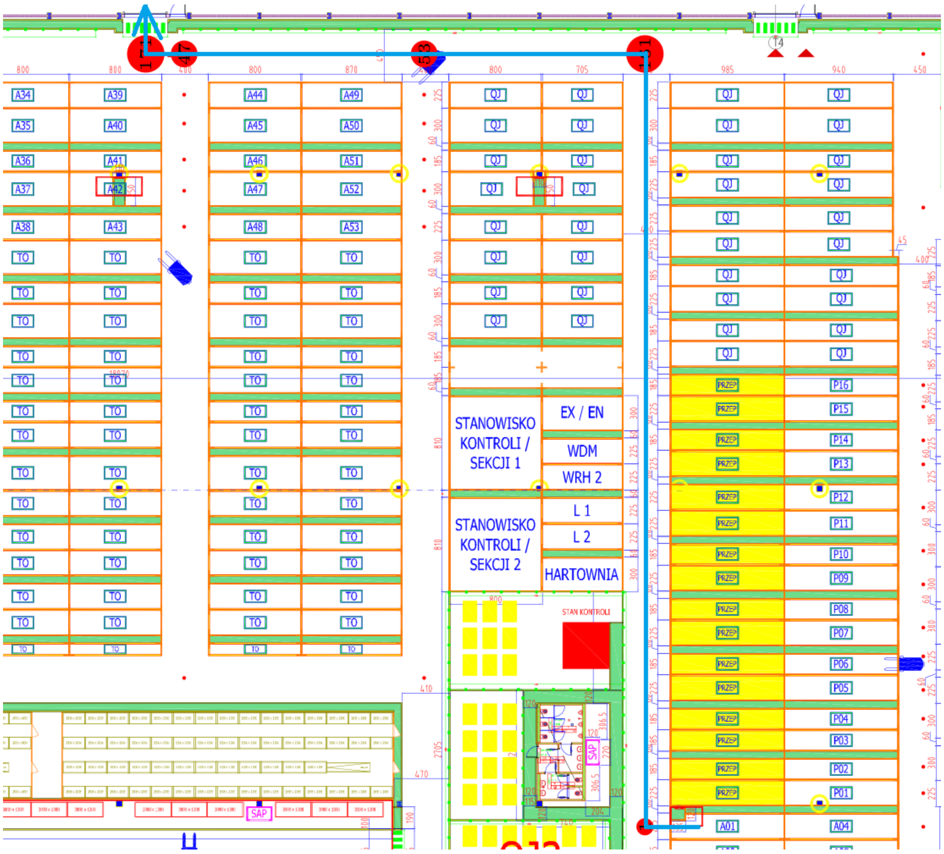

Figure C.5. Route from A01 to TF4

Node	X	Y	Distance to drive [m]	Driving time [min]	Total time [min]
A01	148,3	31,7	2,4	0,028	9,99
1	146,3	30,5	66,1	0,793	
161	146,3	96,6	18,9	0,227	
53	127,4	96,6	20,5	0,246	
47	106,9	96,6	3,3	0,040	
171	103,6	96,6	3,27	0,039	
TF4	103,6	99,9	3,27		11,36

Table C.5. Route from A01 to TF4

C.1.6 TF4 to S001

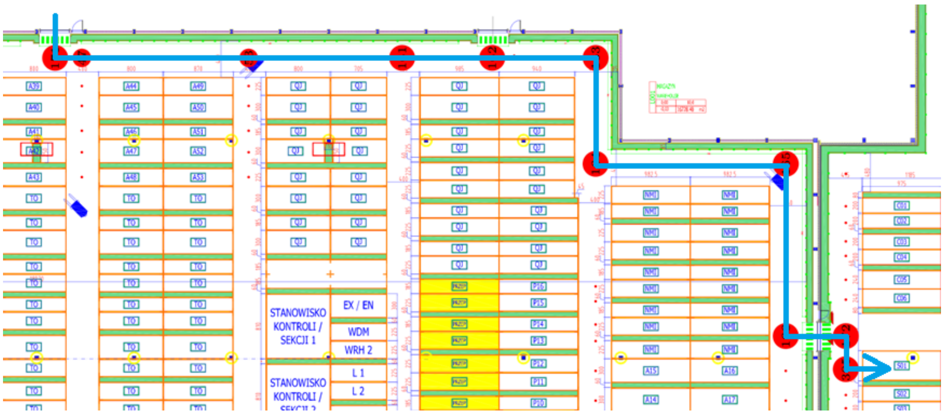

Figure C.6. Route from TF4 to S001

Node	X	Y	Distance to drive [m]	Driving time [min]	Total time [min]
TF4	103,6	99,9	3,27	0,039	11,36
171	103,6	96,6	3,3	0,040	
47	106,9	96,6	20,5	0,246	
53	127,4	96,6	18,9	0,227	
161	146,3	96,6	11,1	0,133	
162	157,4	96,6	12,7	0,152	
163	170,1	96,6	13,2	0,158	
164	170,1	83,4	23,4	0,281	
165	193,5	83,4	21,3	0,256	
166	193,5	62,1	7,4	0,089	
172	200,9	62,1	4,1	0,049	
305	200,9	58	2,6	0,032	
S001	202,95	56,3	2,6		13,05

Table C.6. Route from TF4 to S001

Appendix D

Results

D.1 Case I: Current throughput

Forklifts	Zones [min]	Destination [min]	Origin [min]
3	158,7	407,6	445,9
4	54,3	189,3	303,3
5	31,0	55,6	139,2
6	20,3	34,0	56,4
7	17,6	24,8	34,7
8	16,9	20,5	24,4
9	15,0	17,2	22,2
10	14,4	16,8	22,3
11	13,6	15,6	18,0
12	13,6	15,4	16,8
13	13,0	14,5	15,5
14	12,5	14,0	16,2

Table D.1. Lead time results of Case I

Forklifts	Zones	Destination	Origin
3	97%	98%	98%
4	86%	97%	97%
5	77%	93%	97%
6	62%	86%	81%
7	54%	71%	85%
8	47%	62%	69%
9	43%	54%	66%
10	38%	51%	61%
11	32%	45%	51%
12	32%	43%	49%
13	29%	38%	44%
14	27%	34%	40%

Table D.2. Worked time results of Case I

D.2 Case II: Future throughput

Forklifts	Zones [min]	Destination [min]	Origin [min]
6	150.7	156.2	244.7
7	142.5	152.2	183.5
8	80.2	123.6	139.7
9	72.1	114.9	126.8
10	60.8	105.3	121.1
11	52.8	104.9	115.9
12	18.7	78.4	112.2
13	16.8	74.0	108.4
14	18.5	44.9	95.2
15	19.7	24.3	76.2
16	18.1	12.6	62.7
17	18.1	14.8	25.6

Table D.3. Lead time results of Case II

Forklifts	Zones	Destination	Origin
6	63%	92%	94%
7	66%	78%	91%
8	60%	70%	84%
9	52%	63%	77%
10	45%	61%	74%
11	43%	52%	61%
12	41%	49%	58%
13	38%	47%	56%
14	36%	43%	54%
15	34%	41%	49%
16	31%	36%	47%
17	30%	36%	45%

Table D.4. Worked time results of Case II

Appendix E

Process Definition Language (PDL)

E.1 Elements

Forklift

Width [m]	// Width of the Forklift
Length [m]	// Length of the Forklift
Forklength [m]	// Length of the Forks
Capacity [kg]	// Maximum weight the Forklift can lift
process	
drive	

SKU

Product type	// Type of product in SKU
Container type	// Type of container
Origin	// Where the SKU entered the warehouse
Destination	// Where the SKU will leave the warehouse
Storage location	// Where the SKU will be stored
Delivery time	// Time the SKU needs to be delivered

Storage

X	// X-location of the Storage bin
Y	// Y-location of the Storage bin
dX	// Size in X direction
dY	// Size in Y direction
Remaining space	// Space remaining for storage

Staging

X	// X-location of the Staging lane
Y	// Y-location of the Staging lane
dX	// Size in X direction
dY	// Size in Y direction
Batch	// Batch currently being staged

Node

X	// X-location of the Node
Y	// Y-location of the Node

Arc

Node 1	// One of the Nodes connected
Node 2	// Another Node connected

Product

Stock distribution	// Distribution of starting inventory in the warehouse

Transfer zone

Location	// Node on which the Transfer zone is located

Task

Start	// Location where the SKU is
End	// Location where the SKU needs to go
SKU	// SKU to move

Zone

Product type	// Type of product stored in this Zone
Set of Storage bins in Zone	// Al Storage bins in the Zone

Batch

Shipment time	// Shipment time
Staging lane	// Staging lane from where the batch will depart
Set of SKUs in the batch	// All SKUs in the batch

process

WMS

process

Forklift Management

process

E.2 Processes

- Function Storage location

Zones

// Check zone for available storage locations

for all storages in zone

if space = available and time ≥ deliverytime then

Add storage to LocationQ

else if space = available and time ≤ deliverytime then

Add storage to LocationXQ

if Zone = full then

for all storage

if space = available and time ≥ deliverytime then

Add storage to Location2Q

else if space = available and time ≤ deliverytime then

Add storage to Location2XQ

// Select storage location

if LocationQ.length>0 then

MyStorage is first element of LocationQ

else if LocationQ.length=0 and LocationXQ.length>0 then

MyStorage is first element of LocationXQ

else if LocationQ.length=0 and LocationXQ.length=0 and Location2Q.length>0 then

MyStorage is first element of Location2Q

else if LocationQ.length=0 and LocationXQ.length=0 and Location2Q.length=0 and Location2XQ.length>0 then

MyStorage is first element of Location2XQ

Result is MyStorage

Near Destination

// Check for available storage locations

if destination ≠ staging lane then

MyClient = destination
for MyClient.ToQ
if space = available and time ≥ deliverytime
Add storage to DistQ sorted on distance
Add storage to TimeQ sorted on time
Criteria = index of DistQ + index of TimeQ
Add storage to LocationQ sorted on Criteria
else if destination = staging lane then
MyStaginglane = destination
for MyStagingLane.distanceQ
if space = available and time ≥ deliverytime
Add storage to DistQ sorted on distance
Add storage to TimeQ sorted on time
Criteria=index of DistQ + index of TimeQ
Add storage to LocationQ sorted on Criteria

MyStorage is first element of LocationQ

Result is MyStorage

Near Origin

MyClient=origin
for MyClient.FromQ
if space = available and time ≥ deliverytime
Add storage to DistQ sorted on distance
Add storage to TimeQ sorted on time
Criteria=index of DistQ + index of TimeQ
Add storage to LocationQ sorted on Criteria

MyStorage is first element of LocationQ

Result is MyStorage

- Function Destination

Check all Clients for demand for this product type

Calculate probability for destinations

Generate random number between 0 and 1

Select destination based on random number and probabilities

- Function Distance

Add all nodes to CheckQ

Remove BeginNode from CheckQ

Add BeginNode to CheckedQ

While EndNode is in CheckQ do

CheckedNode is CheckedQ.first

for all nodes in CheckedQ

Check all Arcs from CheckedNode for Nodes in CheckQ

If Distance of node $\geq$ CheckedNode distance

Change distances to CheckedNode distance + Arclength

Add sorted on DistQ

MyNode is First of DistQ

Add MyNode to CheckedQ

Remove from DistQ and CheckQ

Result is Distance of EndNode

- Client

Supply

if Client is not in batch then

CreateSKU

Hold for $\left(\frac{24hours}{\text{number of SKU per day}}\right)$

else if Client is in batch then

Number of SKU = SKUIn.Sample

for SKUSample do

Select Product type

CreateSKU

Hold for $\left(\frac{24hours}{\text{number of batches per day}}\right)$

Demand

if Client is not in batch then

Select next inbound SKU

Hold until one hour before deliverytime

Create retrieval task

else if Client is in batch then

See Batch

- Forklift

Process

// Drive to start

if Location<>Origin of Task then

Calculate Route

Drive

// Pick up SKU

if Task = store then

Remove SKU from transferzone

else if Task = retrieve then

Remove SKU from storage

Hold Pick time

// Drive to destination

Calculate Route

Drive

// Put away SKU

if Destination = storage then

Add SKU to storage

else if Destination = transferzone then

Add SKU to transferzone

else if Destination = staging lane then

Add SKU to staging lane

Hold Put away time

Resume Forklift management

Drive

Node1 is first element of Route

for length of Route do

Node2 is successor of Node1 in Route

Select Arc between nodes

Hold $\left(\frac{ArcLength}{Forkliftspeed}\right)$

Remove Node1 from Route

Node1 is Node2

- Batch

Check if all SKU are present

if FALSE then

Create Rush SKU

Hold until all SKU are present

Free all SKU in batch

- WMS

Sort all tasks on time in TimeQ

Select first task from TimeQ

Hold until Releasetime

Remove Task from WMStaskQ

Add Task to TaskQ

Resume Forklift management

- Forklift management

  Wait until there are Tasks in TaskQ

    Wait until there are Forklifts in ForkliftQ

      Mytask is first element in TaskQ

      Select Forklift based on distance

      Resume Forklift