STREAMLINING THE MATERIAL HANDLING FLOW AT BOLK LOGISTICS

Master Thesis

Niek Tijink
Industrial Engineering & Management

UNIVERSITY OF TWENTE.

BOLK TRANSPORT

STREAMLINING THE MATERIAL HANDLING FLOW AT BOLK LOGISTICS

Author	Niek Tijink
Educational institution	University of Twente
Education	Industrial Engineering and Management
Specialization	Production and Logistics Management
Company	Bolk Logistics B.V.
Address	Zuidelijke Havenweg 2 7554 RR Hengelo
Company supervisor	Jan Bökkers Warehouse supervisor
University supervisors	Dr. P.C. Schuur (1st supervisor) Dr. I. Seyran Topan (2nd supervisor)

Date	05-12-2019
Version	1
Number of pages	83

UNIVERSITY OF TWENTE.

BOLK TRANSPORT

Management Summary

Bolk Logistics is a subsidiary from Bolk Transport B.V. and is specialized in logistics services. Since September 2018, Bolk Logistics Hengelo has a contract with Nouryon chemicals to provide all logistical services for Nouryon Hengelo. Bolk Logistics allocated three warehouse halls for this contract. This research is focused on the logistical services provided for Nouryon, with a main focus point on warehousing.

Problem statement

Since Bolk logistics was rather unexperienced in the field of warehousing before the contract with Nouryon, the process design contains a number of inefficiencies. The main research goal is therefore defined as follows:

To find adaptions in the process design at Bolk Logistics Hengelo that streamline the material handling flow within the warehouse.

Bolk Logistics is paid a fixed amount for each performed action, such as picking, putting away and loading of pallets. Since Bolk Logistics has no influence on the amount of incoming and outgoing pallets, the income of the operation cannot be increased by Bolk Logistics. This means that in order to increase profit, costs must be decreased. With the help of a problem cluster, three core problems that lead to high personnel costs are identified:

1) Storage policy not optimized
2) Picking policy not optimized
3) Scheduling policy for releasing rides for picking unable to cope with stochasticity

Storage and picking policies

In literature, no single suitable method for storing products is found for the situation at Bolk Logistics. Therefore, we developed an binary integer programming (BIP) model which is a combination between an order oriented slotting strategy (OOS) and a cube per order index strategy (COI). OOS is a storage strategy that stores products that are often ordered together close to each other. COI bases the storage decision on the ratio of the storage space needed to store the product to its popularity. We introduce a class based storage policy with ten storage zones in the bulk storage. Since the BIP model is too large to solve optimally, we develop a simulated annealing algorithm to find an allocation of products to storage zones.

The warehouse in Hengelo has fourteen loading docks which are only used for outbound rides. Each ride is coupled to a loading dock at the moment the ride is released for picking. The choice for an outbound loading dock affects the picking time for warehouse workers strongly. Currently, the loading dock is chosen at random by the desk employee. By providing advice on the closest dock based on real-time data, the desk employee is able to select the loading dock which minimizes driving distance.

In theory, by a combination of the new dock allocation and the new storage policy, Bolk Logistics is able to reduce travel distance within the warehouse with 32.6%. This reduction only holds for the in- and outbound material flows in the bulk storage zone. According to management, workers spend approximately two-thirds of the material flow process driving. This implies that our improvements could cut the total workload of warehouse workers by more than 20%.

However, due to a number of assumptions, it is unrealistic to expect the same improvements in practice. The main assumptions here are that the dock that minimizes driving distance is always available, storage zones are never full and that there is no stochasticity.

Scheduling policy for releasing rides

Adapting the scheduling policy for releasing rides for picking will help realizing the improvements from the policies above. As soon as a ride is released for picking on a loading dock, that loading dock is occupied. Currently, the desk employee releases a new ride for picking as soon as a dock is free. In practice, this means that almost always all fourteen loading docks are occupied. We define eight alternative scheduling policies for releasing rides for picking and evaluate them with a simulation study. All policies are compared based on KPIs in five dimensions:

1) Internal efficiency
2) Flexibility of the operation
3) Balance of workload over the day
4) External carrier satisfaction
5) Implementability

After comparing all alternatives, we conclude that scheduling policy four performs best. This policy releases rides for picking when:

- The external carrier arrives at the warehouse for loading.
- The expected picking time before the booking time of the ride is reached (only for rides with an expected picking time over 50 minutes).
- The booking time of the ride is reached (only for rides with an expected picking time under 50 minutes).

Conclusions and recommendations

Looking back at our research goal, we can conclude that we found three adaptions in the process design at Bolk Logistics that streamline the material handling process within the warehouse:

1) A storage policy with class based storage with ten storage zones within the bulk storage
2) An advice for dock assignment based on real-time data
3) A policy which releases rides for picking at the right moment at the right loading dock

The first two adaptions are already implemented in the warehouse. The storage policy is implemented in the Warehouse Management System. In coordination with the warehouse supervisor, we implemented the class-based storage policy with 6 bulk storage zones instead of 10 zones as suggested by our research. Using 6 zones accelerates the adaption period and makes adjustments easier. All products are grouped into the six zones. After an initial analysis, we see that the average utilization of a bulk storage location improved from 73% to 81%.

The dock assignment is implemented with an BI tool which uses real time data from the WMS to calculate the optimal dock assignment for each order of the day. This tool is updated regularly and used by the operational planner and desk employee to schedule rides throughout the day.

The new policy for releasing rides for picking is so far only tested in simulation study. It is therefore recommended to test this policy in practice during a pilot period. It is advised to include one of the authors of this research in this pilot period. Because the policy is not tested in the real system, it is likely that the policy needs to be adapted to function as designed. The design of the policy for releasing rides for picking remains an iterative process.

UNIVERSITY OF TWENTE.

BOLK TRANSPORT

Preface

This thesis is the final part of my study Industrial Engineering and Management at the University of Twente. Here I followed the specialization Production and Logistics Management with a lot of joy. After a pleasant period at Bolk Logistics, I look back at an educative five years. In this preface I would like to thank a number of people.

First of all I want to thank all employees at Bolk Logistics Hengelo for their contributions. Their open attitude enabled me to learn the process quickly in my first months. I especially want to thank my first supervisor, Jan Bökkers, for his effort during my graduation project. He always managed to give an alternative view on a problem. Furthermore I am grateful for the opportunity Bolk offers to start my career at their organization.

Secondly, I want to thank my supervisors at the University. I thank Peter Schuur for all guidance throughout the Master Thesis. His expertise and feedback really helped me during this period. I also want to thank Ipek Seyran Topan as my second supervisor whose feedback was helpful in the last stages of the thesis.

Finally, I thank my friends and family for their support throughout all these years of my education. They helped me to stay motivated and to enjoy my time.

Niek Tijink, December 2019

Table of contents

List of figures

List of tables

Glossary

BIP	Binary integer programming
COI	Cube per order index
CTT	Combi Terminal Twente (Container processing)
KPI	Key performance indicator
OOS	Order oriented slotting
Ride	One truckload or one container, can contain multiple customer orders
SA	Simulated Annealing
Carrier X	External carrier who couples and decouples trailers for rides of the following day
WMS	Warehouse Management System

1. Introduction

In this report my research study at Bolk Logistics Hengelo is presented. The research focuses on the logistical services provided by Bolk Logistics Hengelo for Nouryon Hengelo, a producer of consumer salts. More specifically, the research focuses streamlining the material handling at the warehouse in Hengelo.

This chapter starts with an introduction of the company Bolk Logistics in section 1.1. A quick look in the process for Nouryon is given. The motivation for research is explained in section 1.2. Based on the motivation for research and an initial analysis, core problems are formulated in section 1.3. The research goals are stated in section 1.4. Section 1.5 states the research design with all secondary research questions.

1.1 Company Introduction

Bolk Logistics is a subsidiary of Bolk Transport B.V.. Bolks' core business is the transport of goods for third parties within Europe. Bolk was founded in 1934 as a family business in Almelo. Until the 80's, Bolk focused solely on transport over the road. In 1985, Bolk started with the transfers of sea containers onto trucks that were transported to Almelo by train. At the end of the 90's, sea containers no longer were transported inland by train. Therefore, Combi Terminal Twente (CTT) was founded to facilitate the transport of containers via inland shipping.
Recently, Bolk is specializing in different transport markets. One of the new markets is the transport of exceptional goods, such as windmill parts and large silos. Furthermore, Bolk is focusing more on providing logistical services and warehousing.

For the specialization in logistical services and warehouse, Bolk Logistics was founded in 2015. Bolk Logistics has warehouses in Almelo and Hengelo. This research solely focuses on the latter. The core business of Bolk logistics consists of logistical services based on storage of goods and transfer of goods. The warehouse in Almelo is a public warehouse, which means that the warehouse facilitates multiple businesses. In Hengelo, on the other hand, the warehouse is contracted. In this case, businesses rent one hall (or multiple halls) of the warehouse from Bolk Logistics. The business is then responsible for the operations within the hall. If desired, equipment can be rented from Bolk Logistics. Most of the halls in Hengelo are utilised in this manner. Other customers require extra services. In Hengelo, Bolk Logistics provides extra services, such as 'Value Added Logistics (VAL)' and performance analysis of customers of the warehouse.

A special case within the warehouse in Hengelo is the contract between Nouryon and Bolk Logistics. Nouryon, formerly known as AkzoNobel, is a producer of chemical products. In Hengelo, Nouryon mainly produces consumer salts. Bolk Logistics has taken over all logistical operations of consumable salts of Nouryon in Hengelo since September 2018. This means that Nouryon only produces and sells the products. Bolk Logistics is responsible for the transport from the production site to the warehouse, the storage of products and for the transport from the warehouse into the trucks and containers. The transport by truck to customers is done by third parties contracted by Nouryon. Transport over water is managed by Combi Terminal Twente (CTT), which is also a subsidiary of Bolk Transport B.V., just as Bolk Logistics. For a graphical overview of the situation in Hengelo, see figure 1.

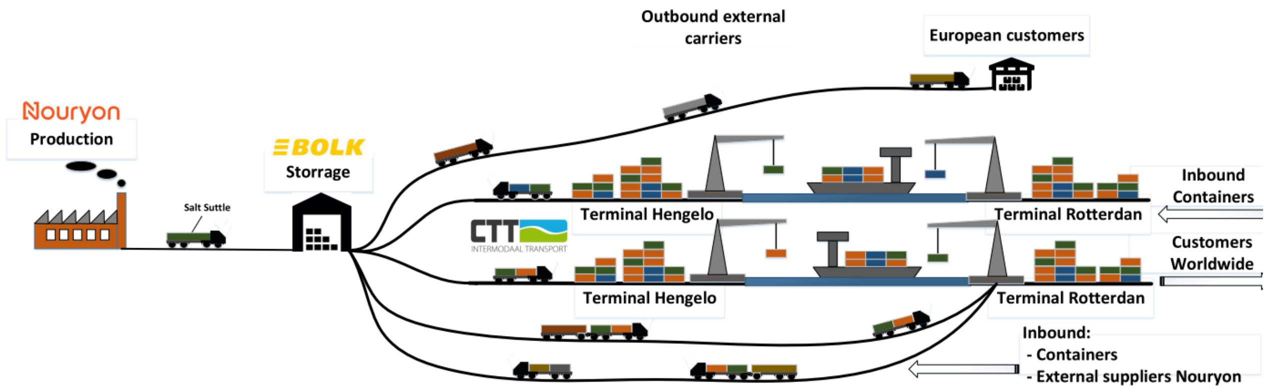

Figure 1: Schematic overview flow of goods for Bolk Logistics Hengelo (Bolk Logistics, 2019)

1.1.1 Quick look into the process

Bolk Logistics is responsible for all logistics operations regarding Nouryon. Finished products – Nouryon only produces full pallets – are automatically loaded from an automatic transport line into a shuttle truck. The shuttle truck then drives to the warehouse located near to the production site where all pallets are automatically unloaded onto a conveyor belt. Warehouse staff pick pallets from the conveyor belt and store them at their destined location.

For each customer order Nouryon contracts a third party for transport to the customer. The third party carrier then books a timeslot at the warehouse for loading. Sometime before an order is scheduled to be picked up, warehouse staff begins picking the order. The pallets are then placed at a set-up outbound area in front of the loading dock. When the carrier arrives, the pallets are loaded from the set-up outbound area into the truck or container.

The entire process is explained in more detail in Chapter 2.

1.2 Motivation for Research

Bolk, in the past, used to be focused only on transport. Since starting Bolk Logistics, warehousing is added to their activities. Because of little experience in the warehousing field, this initially led to a lot of inefficiencies in the process. The extreme inefficiencies are already dissolved, but a lot of smaller inefficiencies remain. As a result, the contract with Nouryon has not been as lucrative as was hoped on beforehand.

In the contract with Nouryon, price agreements were made for five years (2018-2023). A fixed amount of money is paid for each action (inbound, storage, outbound, loading, shuttle truck transport and administration). Since the production and sales are done by Nouryon, and not by Bolk Logistics, Bolk Logistics has no influence on the number of actions performed. As a consequence they have no influence on the revenue of the operation. Therefore, reducing costs is the only way to increase profits.

According to management, costs can mostly be cut by reducing the workload in and around the warehouse. Inside the warehouse, warehouse workers often drive more than strictly necessary. Most of these unnecessary driving meters are consequences of simplicities in the warehouse management system (WMS). Around the warehouse, workload can be reduced by automating administrative tasks. Bolk Logistics uses a number of information systems who are not (yet) compatible with each other. As a consequence, a lot of administrative actions have to performed twice or thrice.

Besides lowering the total workload, workload should be more balanced throughout the day and week. One of the main problems is the peak load for the order pickers in the warehouse. Third party carriers, especially those that have deliveries abroad, often arrive earlier or later than the timeslot that was booked.

This leads to uncertainty in the outbound logistics. The production at Nouryon is unstable as well and they often deviate from the provided forecasted production. This leads to uncertainty in the inbound logistics. Together, the in- and outbound logistics lead to high peak loads in the warehouse. By smoothening the workload, management hopes to cut personnel costs inside the warehouse.

1.3 Problem Statement

With the help of a problem cluster, we are able to identify core problems. A core problem is the root cause of the observed problem (Heerkens and Van Winden, 2017). In our case, the main observed problem is the high cost of personnel. To identify core problems, we created a problem cluster (figure 2). In this problem cluster, the observed problem is coloured blue, core problems which cannot be influenced are coloured red and core problems which can be influenced are coloured green.

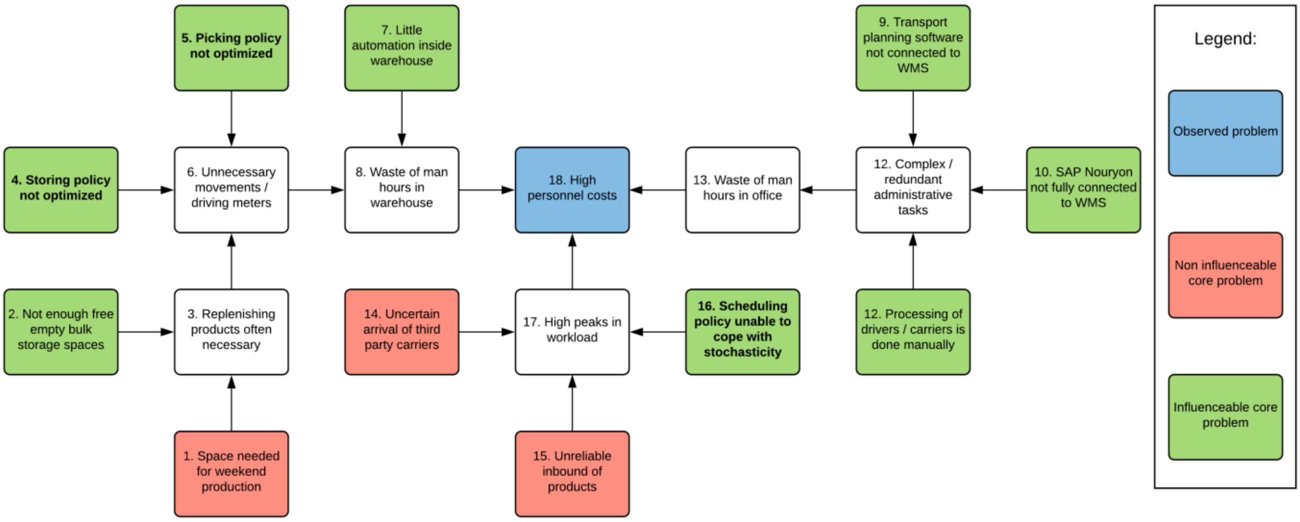

Figure 2: problem cluster at Bolk Logistics

The high personnel costs at Bolk Logistics (18) – the observed problem – can be lowered in three ways. First, the waste of man-hours of warehouse staff can be decreased. Problems (1) to (8) in the problem cluster lead to unnecessary work for warehouse staff. Due to little automation inside the warehouse (7), each action within the warehouse needs an operator. No single action is automated. Warehouse staff often drive more than strictly necessary (6) due to unoptimized picking (5) and storing (4) policies. In addition, replenishing of products is often needed (1-3). Secondly, personnel costs can be cut by increasing productivity in the office by decreasing the waste of man hours (13). By automating driver processing (12) and connecting different IT systems (9, 10), complex and/or redundant tasks (12) can be made obsolete. Thirdly and lastly, personnel costs can be decreased by balancing workload for warehouse staff (17). Peak loads occur because of unreliable inbound from Nouryon (15) and uncertain arrival of third party carriers for outbound logistics (14). The only way to manage workload is with a policy for releasing rides for picking in outbound logistics (16). The current policy is unable to manage the workload.

In figure 2, we see eight potential core problems. Connecting different IT systems and automating tasks between them are not suited well for research within our field of expertise. Therefore, problems (9) and (10) are discarded. From the remaining six potential core problems, we select the one(s) with the highest potential. Problems (7) and (12) are related to automating tasks. Both of the probable solutions, automated guided vehicles for (7) and an automated planning system for (12), are expensive while the potential savings are not very high. Therefore, we disregard core problems (7) and (12) as well. Replenishing (3), aggregating products from different storage locations or relocating pallets to pallet racks, is (usually) only necessary when mistakes are made earlier in the storing process. Therefore, we disregard problem (2) as well. The three remaining problems are the core problems with the highest potential. In this research we will tackle the three remaining core problems:

1. (4) Storing policy not optimized
2. (5) Picking policy not optimized
3. (16) Scheduling policy unable to cope with stochasticity

The first two core problems focus on decreasing the total workload for warehouse workers, while the third core problem tackles the workload peaks for warehouse workers.

1.4 Research goal

The research goal is:

To find adaptions in the process design at Bolk Logistics Hengelo that streamline the material handling flow within the warehouse.

The research goal can be subdivided into two goals:

1. To lower the total workload within the warehouse by aligning processes in material handling.
2. To balance material handling by developing a new policy for releasing rides for picking

1.5 Research Design

1. *How is the current situation at Bolk Logistics?*
   Chapter 2 discusses the current situation at the warehouse of Bolk Logistics Hengelo regarding …
   a) the current overall operation at Bolk Logistics Hengelo
   b) the current inbound logistics
   c) the current outbound logistics
   d) the current scheduling of outbound logistics
   e) the current workforce management

2. *What can we learn from literature that can support our research?*
   Chapter 3 describes our literature review. Literature is consulted to gain more knowledge on the following subjects:
   a) Warehouse classification
   b) Storage methods
   c) Optimization techniques

3. *How can we lower the total workload by changing warehouse operations?*
   Chapter 4 proposes two solutions to lower the overall workload for warehouse workers. Based on insights from the current situation analysis and from the literature review, we determine heuristics to improve the storage of inbound products, as well as improve the picking distance of outbound products.
   a) How can we develop an improved storage strategy with class based storage?
   b) How can we improve the dock allocation for outbound rides?

4. *How can we balance workload with a new policy for releasing rides for picking?*
   Chapter 5 proposes scheduling policies for releasing rides for picking that can cope with stochasticity of carrier arrival. The goal of the new scheduling policy is to streamline the material handling process in the warehouse. Key performance indicators are divided into five dimensions:
   - Flexibility of the operation
   - Efficiency of the operation
   - Balance of the workload
   - Satisfaction of external carriers
   - Implementability of the new policy

   Chapter 6 evaluates the policies defined in chapter 5 by means of a simulation study based on performance indicators of the five dimensions.

1.5.1 Scope

Due to time limitations, we are unable to take all factors and variables into account. Therefore, we limit the scope to processes that are easily influenceable:

- We take the limited information from Nouryon about incoming products for granted. Earlier attempts to improve communication protocols were proven unsuccessful.
- We take uncertain arrivals from third party carriers for granted. It is hard to motivate external carriers, especially foreign carriers, to arrive as scheduled. Eventual penalties would have to be implemented in coordination with Nouryon, which will be time consuming.

In addition do we limit our research to the warehouse itself. Processes that take place outside the warehouse, such as the transport by shuttle truck, are not taken into account. We also choose to focus on the logistics services for Nouryon in Hengelo solely. Solutions could later be fine-tuned for other locations.

2. Current situation

This chapter analyses the current situation at Bolk Logistics Hengelo. First, relevant processes in the operation for Nouryon Hengelo are explained. Thereafter, numbers and figures are given to quantify the outbound process of the operation. A distinction is made here between the product flow in the warehouse and the scheduling of outbound trucks and containers. Based on the analysis, we define solution proposals to streamline the material handling flow.

Figure 3 schematically shows – a simplified version of – the processes of the logistical services for Nouryon. Throughout this chapter, all relevant elements are explained in more detail.

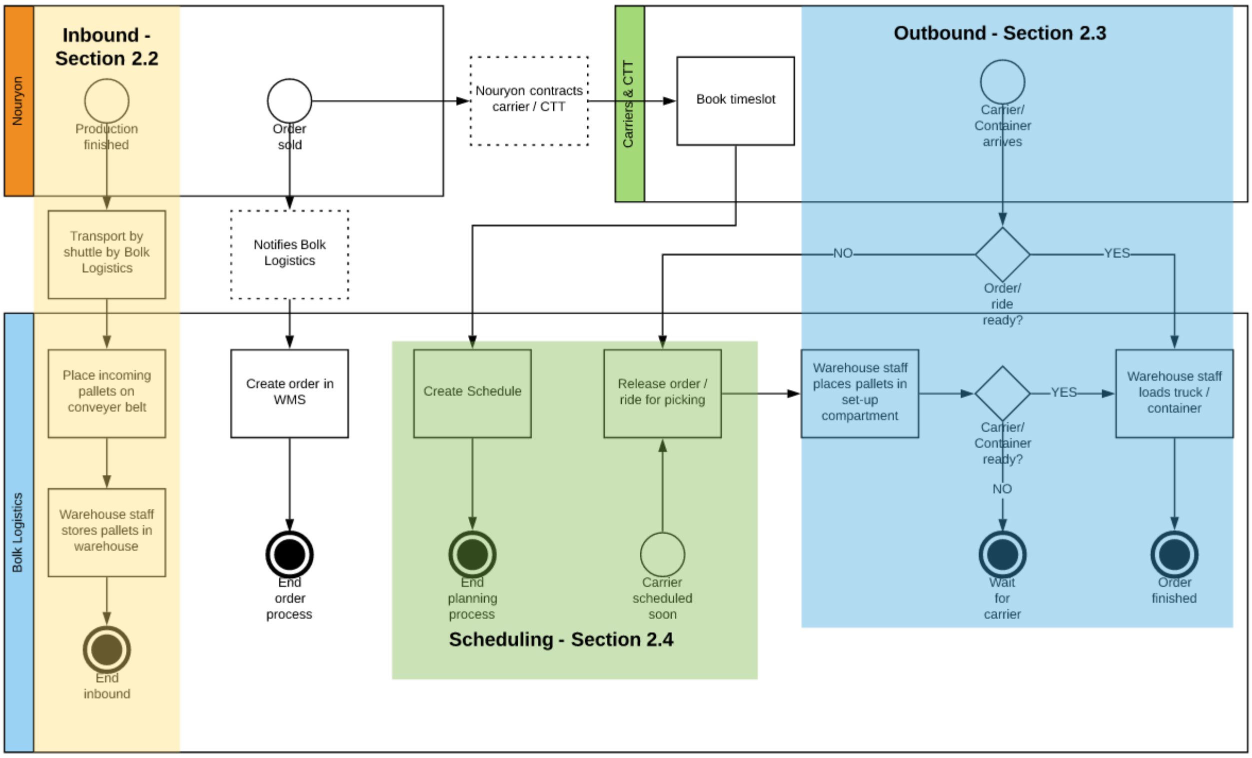

Figure 3: Schematic overview logistical processes

This chapter starts with a short introduction of the warehouse in Hengelo (section 2.1). Section 2.2 focusses on the current situation at the inbound logistics by discussing the current storage method and the number of inbound pallets. Section 2.3 explains the outbound logistics by clarifying the picking and loading process. Subsequently, the scheduling of the outbound logistics (i.e. outgoing trucks and containers) is discussed in section 2.4. Section 2.5 discusses the organization of personnel at the warehouse. At last, Section 2.6 makes concluding remarks on the current situation and proposes three improvements for reducing and/or balancing the workload in the warehouse.

2.1 The warehouse

The warehouse in Hengelo is split up into six halls, of which three are contracted by Nouryon. The other three halls are contracted by different businesses and are irrelevant for our research. Bolk Logistics and Nouryon have contractual agreements about minimum and maximum storage. Bolk Logistics is paid by Nouryon for each performed action, as well as for the storage of products.

A schematic display of the layout of the warehouse is shown in figure 4 on the next page. It can be seen that most of the warehouse is used for bulk storage. In the bulk storage locations, block stacking is used (see figure 5). Because Nouryon only produces and sells full pallets, block stacking is an obvious choice for storage. Normal sized bulk storage locations can store up to 86 pallets depending on stacking height, pallet size and packaging type. To increase capacity and meet contractual agreements, twelve pallet racks are used, each with a storage capacity of 480 pallets (see figure 6). In total, the theoretical storage capacity of the three halls combined is roughly 19,000 pallets.

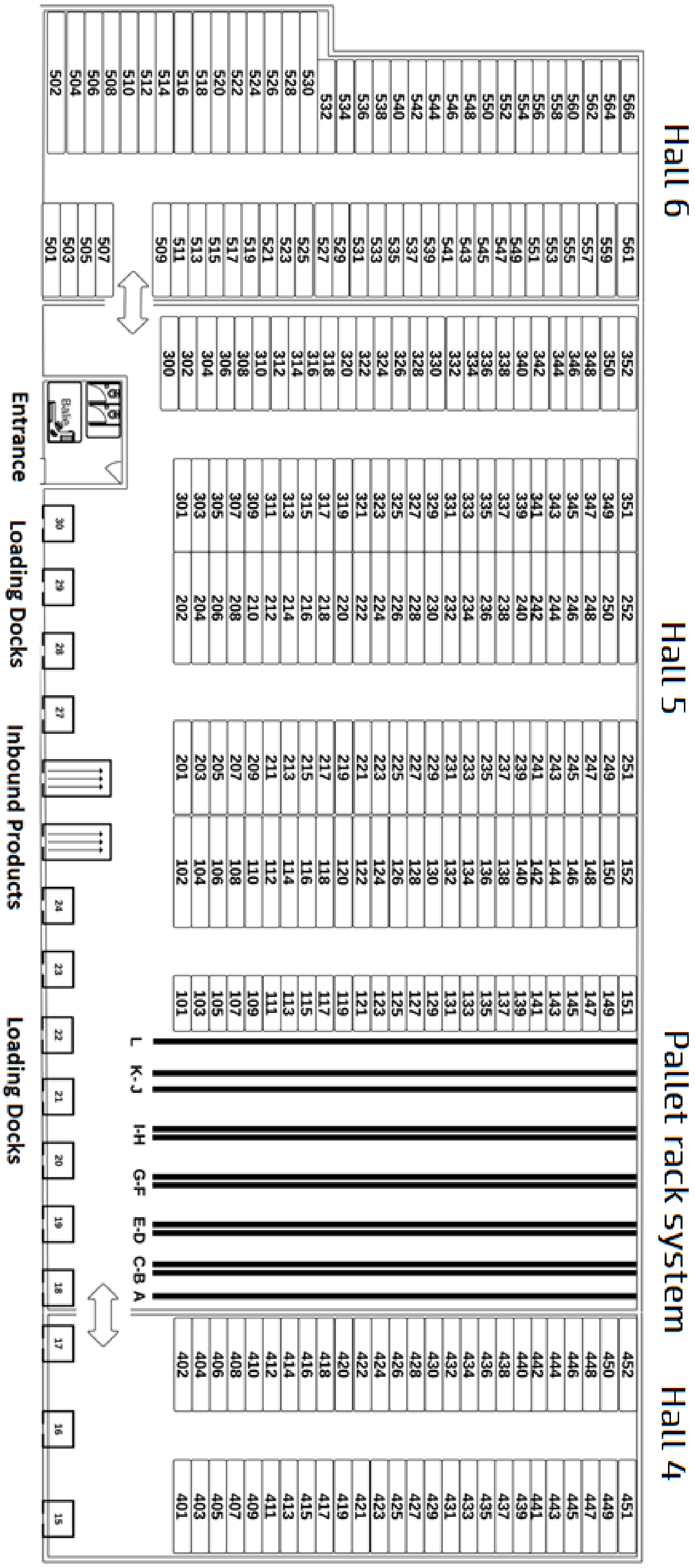

Figure 4: Schematic overview lay-out of the warehouse

Figure 5: Use of block stacking in bulk storage

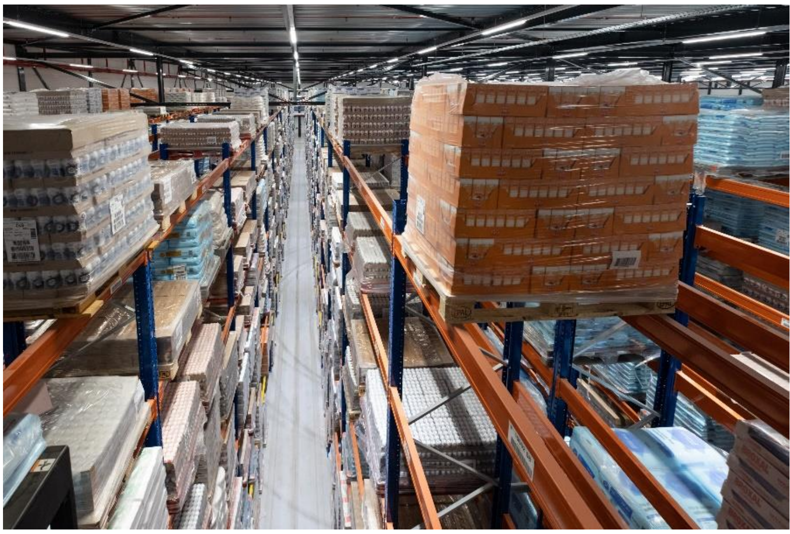

Figure 6: View from above in narrow aisle pallet rack

Pallets are loaded into trucks or containers on one of the fourteen loading docks present in the warehouse. Two of the docks, docks 25 and 26, are solely used for the inbound of products. This process is explained in detail in section 2.2.

Pallets are transported throughout the warehouse on specialized forklifts. These forklifts are able to transport two pallets at the same time by spreading the fork of the forklift (see frontpage). The use of these forklifts increases efficiency compared to single-pallet forklifts. Pallets are loaded into trucks or containers with a regular forklift or with a pump truck. Pallets are placed in, and retrieved from, the pallet racks by a specialized small corridor truck (see figure 7). This truck is able to drive automatically to the correct location of a pallet. The worker then only has to place or retrieve the pallet from the shelve rack.

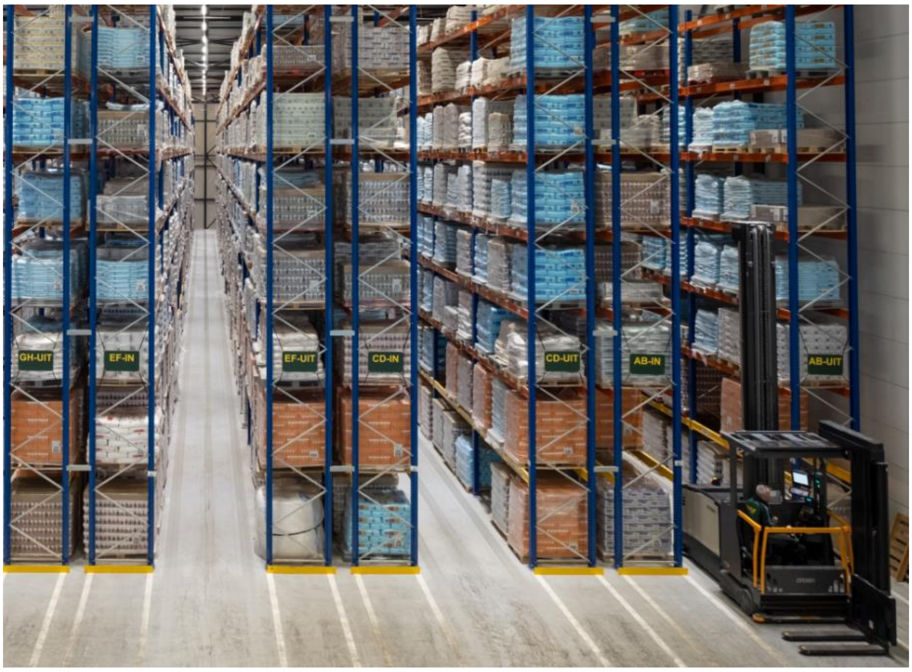

Figure 7: Small corridor truck (right) in front of narrow aisle pallet rack

2.2 Inbound logistics

Nouryon produces on average thousand pallets per day. All these pallets have to be transported from the production facility of Nouryon to the warehouse of Bolk Logistics. This transport is taken care of by Bolk Logistics with its shuttle truck, see figure 8. All produced pallets from all production lines arrive at one central location via an automatic transport line (ATL). At this central location, the pallets are automatically loaded into the shuttle truck. The shuttle truck can at most transport 26 pallets per trip, which would mean that approximately 40 trips per day are required to transport all produced pallets. In practice, we see that this number is a bit higher, approximately two trips per hour (48 per day). Back at the warehouse, pallets in the shuttle truck are automatically unloaded onto a conveyor belt (see figure 5 on the right side). Bolk Logistics has no influence on the production of Nouryon and thus no influence on the amount of inbound pallets. There is no significant buffer on the ATL as well, which means that the shuttle truck needs to keep up with production.

Figure 8: Shuttle truck for transport from production site to warehouse

In the warehouse, pallets are picked from the conveyor belt and stored in the warehouse. The warehouse uses a class-based storage policy with two storage zones: bulk and pallet racks. Since Bolk Logistics uses no dedicated storage, each pallet and each article can be placed in every location within its zone. Pallets are stored in a bulk storage location by batch number. The choice for a specific bulk storage location is made based on minimal driving distance from the arrival point. Order picking distance for outbound logistics is thus not taken into account during the storage of pallets. In addition, there is made no distinction between fast and slow movers, except for the decision whether to store products in the pallet racks. In the pallet racks, pallets are stored randomly by the Warehouse Management System (WMS). However, workers often change the location to a more convenient location in the pallet racks. Figure 9 shows a heatmap of stored products in bulk storage from 1 July till 1 September 2019. From the heatmap, we conclude that the current storage policy leads to high utilization in the front of the warehouse, but not necessarily to many picking activities in the front of the warehouse. In other words, the locations close to the docks are almost always occupied, but their throughput is average.

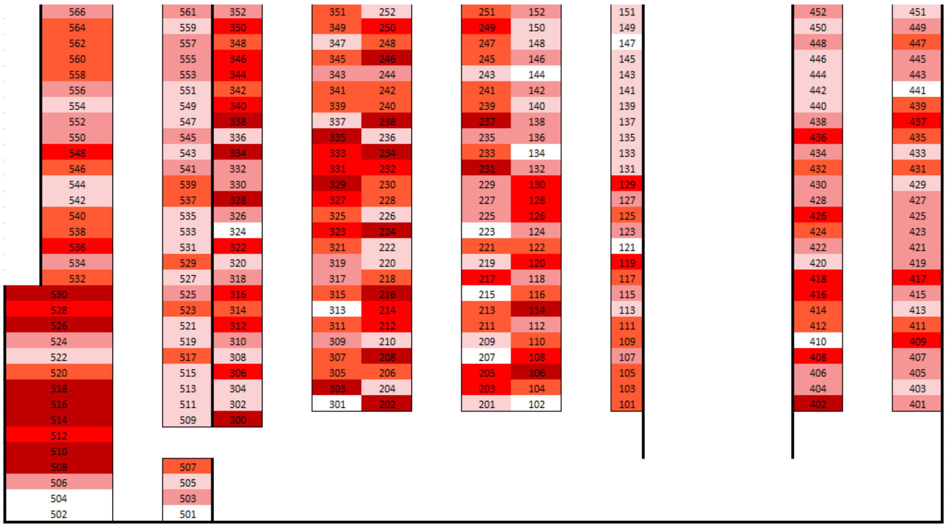

Figure 9: Heatmap of number of stored pallets per bulk storage location

To gain an insight in the production of Nouryon, we compute the time of entry in the warehouse for each pallet for a time span of 9 weeks. The number of pallet arrivals per hour of the day can be seen in figure 10. It can be seen that the influx of pallets is rather stable throughout the day, but that there is a dip around 6:00 and 18:00. This dip can be explained by the shift change for shuttle truck drivers around those times.

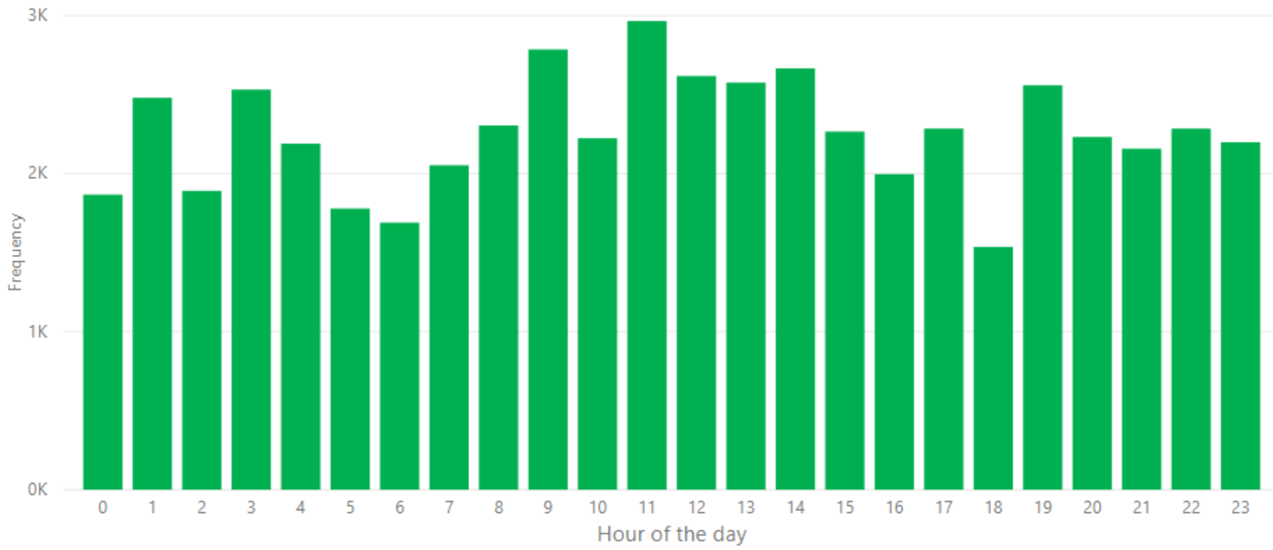

Figure 10: Number of inbound pallets per hour of the day

2.3 Outbound logistics

In the last 10 weeks, 4,453 customer orders left the warehouse in 3,324 trucks or containers containing 70,901 pallets. This means that on average 7090 pallets leave the warehouse per week. All these pallets undergo two actions when leaving the warehouse: picking and loading.

When an order is released for picking and is assigned to a dock, warehouse staff starts picking pallets for the order. Each dock has a set-up outbound area where the customer order is stocked temporarily when picking the order. Only after all pallets are picked, loading of the truck or container can start.

The bulk storage locations are divided in sixteen groups. Each row of locations is divided in three groups, front (_1), middle (_2) and back (_3). In addition, all drop-in and drop-out locations of the pallet rack system are grouped into one group: "Drop". See figure 11 for a graphical overview. Based on historical picking data, we calculated the expected picking time per pallet from each group of locations to each set-up outbound area ("KZV" in Dutch). The historical picking time in seconds for a single pallet from each bulk-group to each

KZV can be seen in table 1. From this table, we deduct that when the driving distance increases, the picking time increases as well. Furthermore, we see that the average picking time of a single pallet is 73 seconds.

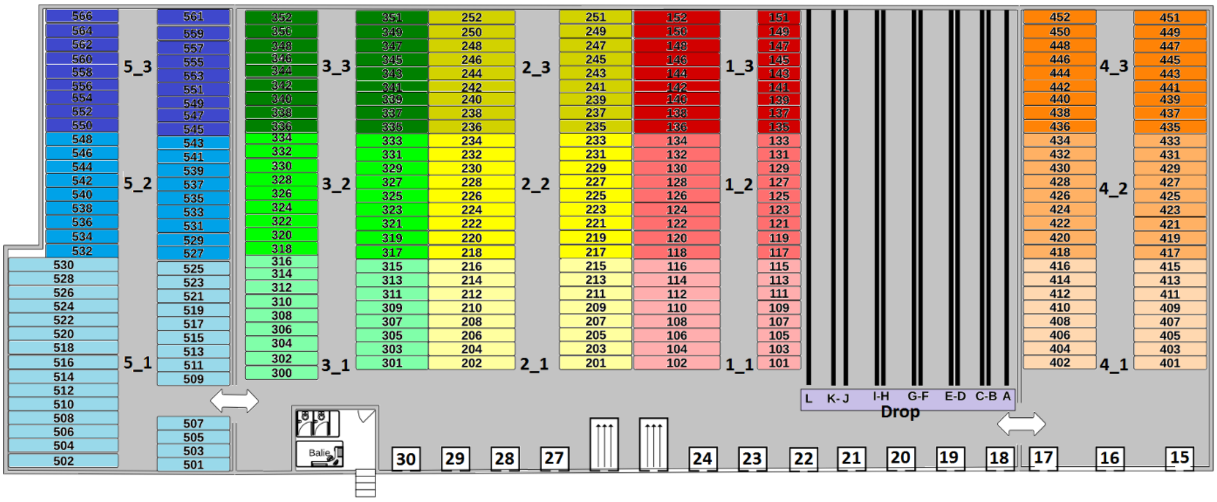

Figure 11: Graphical overview grouped bulk storage locations

Table 1: Picking times per bulk group to each set-up outbound area (= KZV)

BulkGroup	KZV15	KZV16	KZV17	KZV18	KZV19	KZV20	KZV21	KZV22	KZV23	KZV24	KZV27	KZV28	KZV29	KZV30	**Total**
1_1	74	73	69	74	68	65	65	57	55	57	64	64	71	70	**65**
1_2	83	79	84	77	80	73	76	70	64	66	73	79	77	79	**75**
1_3	101	93	97	94	92	92	92	82	87	78	92	95	88	92	**90**
2_1	81	80	81	80	77	74	69	70	68	65	58	59	58	61	**69**
2_2	89	88	87	88	85	81	80	74	76	70	64	68	67	69	**76**
2_3	88	97	94	95	100	94	91	93	81	84	74	76	81	81	**87**
3_1	85	85	88	88	82	81	79	75	75	71	64	60	61	57	**74**
3_2	96	95	97	94	95	89	88	82	83	80	72	70	69	65	**83**
3_3	104	103	105	106	98	95	92	92	89	85	82	77	76	71	**89**
4_1	49	52	56	58	60	64	68	72	73	74	76	85	83	90	**69**
4_2	62	60	62	70	74	75	78	77	78	81	91	92	90	97	**78**
4_3	69	66	71	80	81	80	85	87	90	90	90	99	105	100	**84**
5_1	95	92	88	87	85	82	83	74	72	76	72	66	67	61	**76**
5_2	102	99	102	102	99	96	81	89	87	81	76	76	72	73	**87**
5_3	106	105	112	98	100	99	95	95	95	95	86	85	81	82	**94**
Drop	52	51	50	47	47	47	47	50	51	55	60	64	66	67	**54**
Total	**76**	**76**	**76**	**76**	**76**	**73**	**73**	**71**	**70**	**70**	**70**	**71**	**71**	**72**	**73**

Picking time per pallet in seconds

For the picking logic, it is irrelevant in what order pallets are picked. Forklifts are able to carry at most two pallets of the same product per trip. If only one pallet of a product is needed, the forklift driver can only transport that one pallet due to software restrictions in the WMS. As a result, smarter routing is not an option in the current design. However, picking time and picking distance can be decreased by smarter assigning docks to orders. When looking at the current assignment of docks, we deduct that the dock assignment appears random. Ideally, when an order contains plenty of products from row four (4_1, 4_2, 4_3), the order is assigned to either dock 15, dock 16 or dock 17. However, when looking at the Sankey diagram in figure 12, we see that products from row four are not particularly often loaded at one of those three docks. In the Sankey diagram, the '4' represents the storage groups 4_1, 4_2 and 4_3 from figure 11.

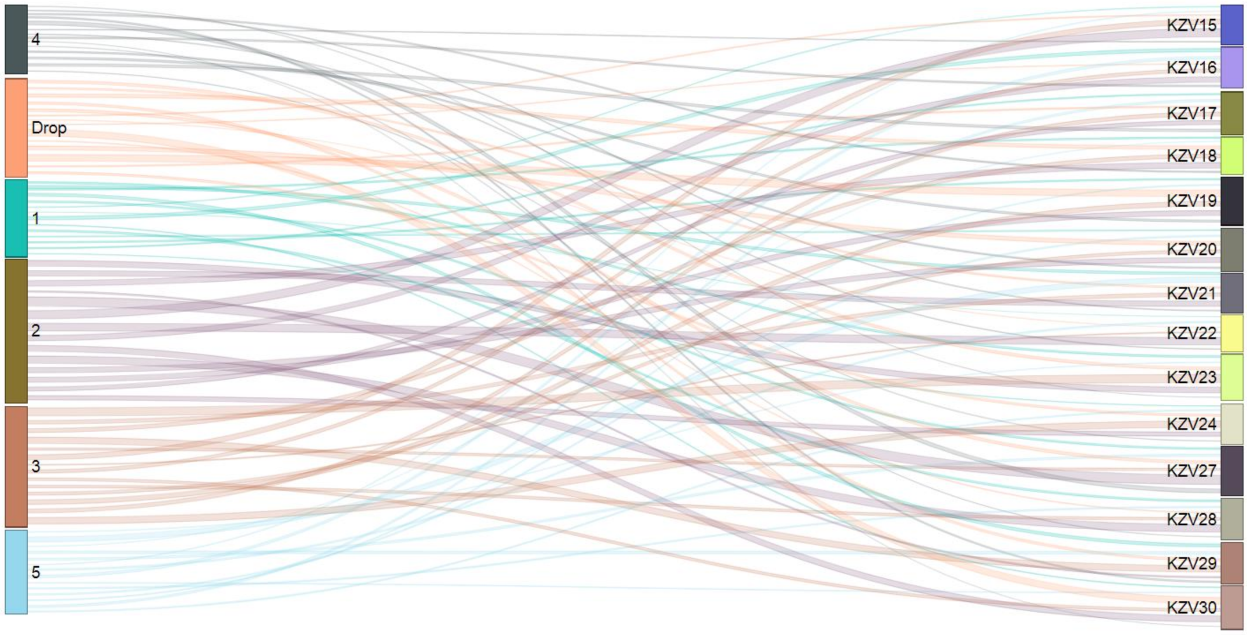

Figure 12: Sankey diagram of material flow throughout the warehouse

When all orders are present at the set-up outbound area (or KZV), the order is ready to be loaded into the container or truck. However, the container or truck has of course to be present at the warehouse before loading can start. Containers or trucks often arrive late and orders are often ready at the set-up outbound area earlier than their booking time. As a result, pallets often have to wait for a long time at the set-up outbound area. The operational planner keeps track of all orders and manages the workflow of the warehouse workers.

Loading time of an order is mainly dependent on the size of the order, because the distance to the dock is almost always equal. However, sometimes multiple orders are transported in a single truck. In that case, it is paramount to load products in a specific way, such that the driver does not have to move around pallets inside the truck. As a result, loading times of rides with multiple orders are often longer. In the histogram of the loading time per pallet (figure 13), we see that the loading time per pallet follows a Bell Curve, except for the peak between 0 and 10 seconds. This peak is however artificial, because it occurs when the warehouse worker scans all pallets first before actually starting to load the ride, instead of scanning each pallet while it is being loaded. As a result, the loading time per pallet is artificially low. When removing such anomalies, we find an average loading time per order of twenty minutes and an average loading time per pallet of 55 seconds.

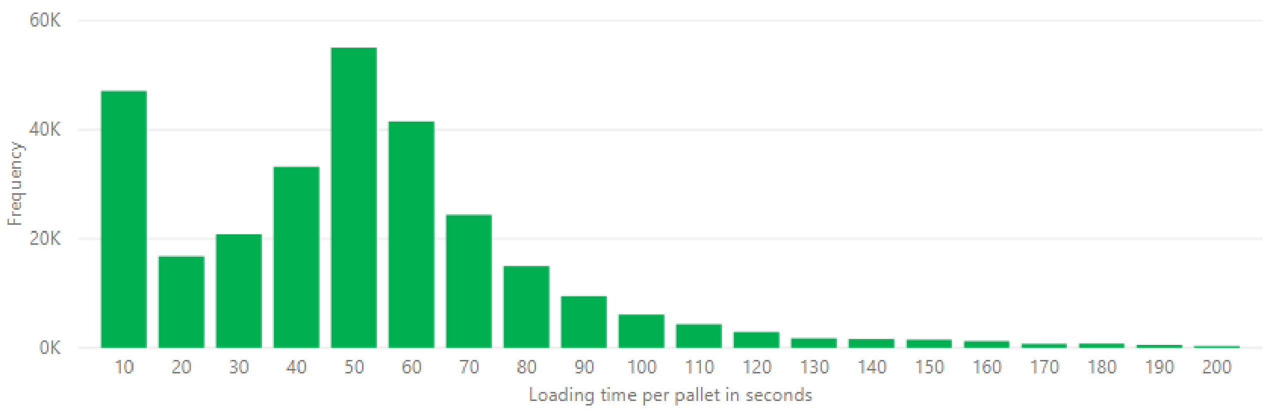

Figure 13: Histogram loading times per pallet in seconds

2.4 Scheduling outbound logistics

One of the main aspects of the outbound logistics is the scheduling of the loading of outgoing trucks and containers. The scheduling policy has a significant impact on the performance inside the warehouse. Bolk Logistics has no influence on the outbound logistics directly. They are however able to schedule the internal logistics to their preference. This holds that the desk employee determines when and where which ride is released for picking.

Nouryon contracts external carriers to transport their products to their customers. For shipments over water, Nouryon books a container at CTT who will carry out the transport. CTT assigns each order a container and schedules each container on a boat. This schedule is communicated with Bolk Logistics, who are responsible for timely loading the container. Transport of truck loads are outsourced by Nouryon to a number of third party carriers. These third party carriers book a timeslot of 40 minutes to load at Bolk Logistics. There however is one exception for the third party carriers. Carrier X is a transporter from the Netherlands who already loads the trucks with delivery day n on day $n-1$. This means that there is at least one employee of Carrier X present who couples, decouples and stores trailers, such that their truck drivers can all leave early in the next morning. Scheduling of the orders for Carrier X is done in coordination with the employee of Carrier X and it does not necessarily follow the timeslot allocation. So, (most) external carriers are (supposed to be) arriving within a fixed timeslot and containers have a due date when they leave on a ship.

On average, 1.5 FTE is tasked with the scheduling and managing of the outbound logistics, as well as managing the warehouse staff. Their main objectives are decreasing waiting times of external carriers and maintaining a workflow in the warehouse (i.e. making sure all warehouse workers have work to do). In addition, they make sure containers for export are loaded on time and they oversee the loading of third party carriers.

Figure 14 shows the logic flow behind releasing rides for picking. This policy is focused on decreasing waiting times for external carriers (excluding Carrier X) and ensuring there is enough work in the pipeline for warehouse staff. The scheduling policy attempts to keep all docks occupied by working ahead. In this way, a buffer is built up which is convenient when a lot of drivers arrive within a short time. Working ahead is often necessary, as can be derived from figure 15, because there are peak moments when a lot of drivers arrive. These peak moment are usually from 8:00 till 10:00 and from 13:00 till 15:00.

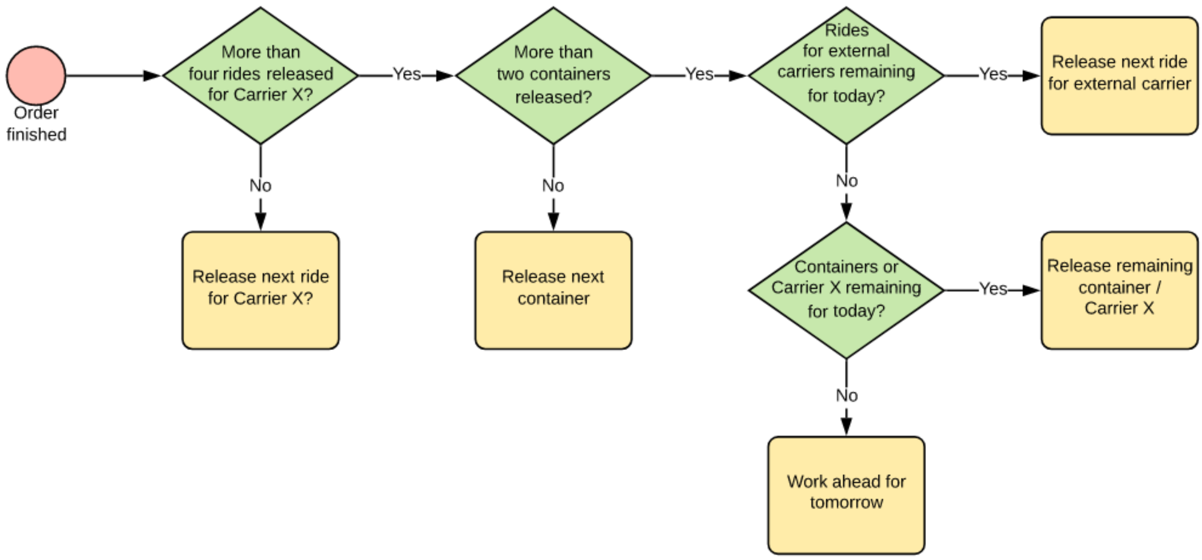

Figure 14: Current policy for releasing rides for picking

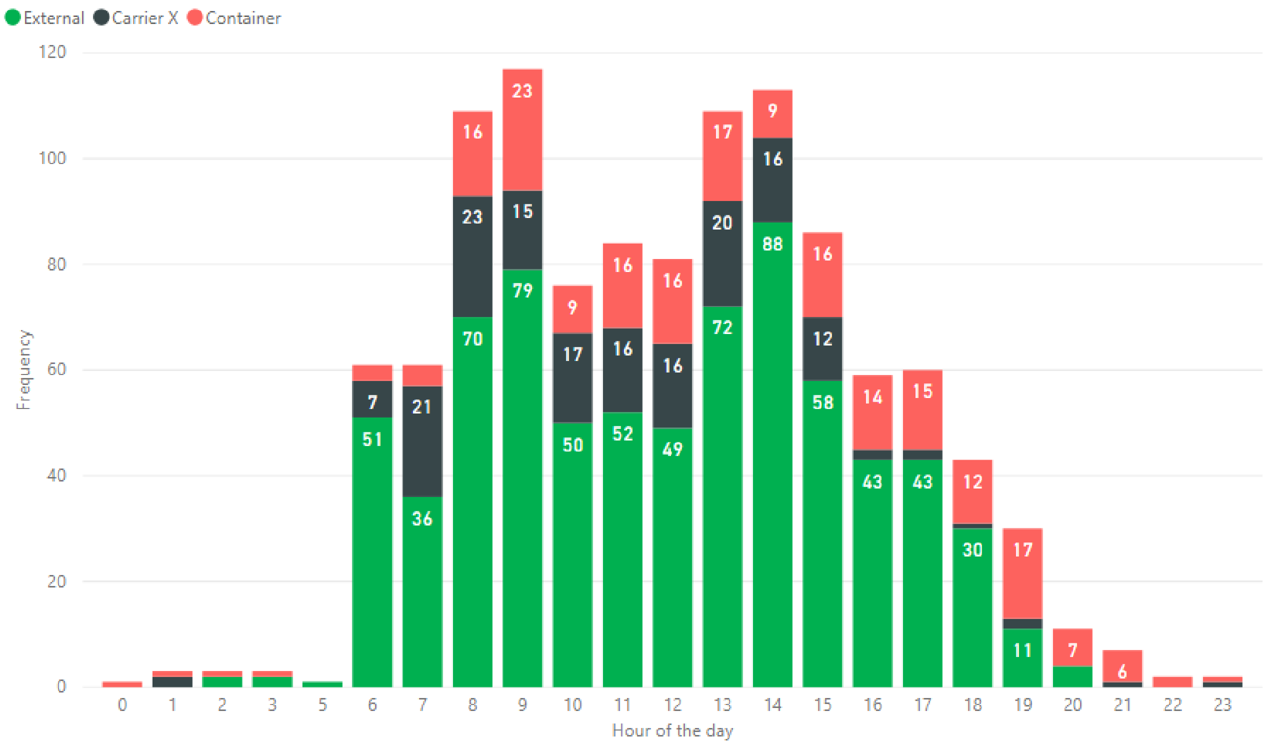

Figure 15: Arrival of drivers per carrier type

Working ahead is very beneficial when variation in upcoming events is low. However, external carriers often arrive earlier or later than scheduled. To visualize the uncertainty in third party carrier arrivals, we create a boxplot (see figure 16) for the average time between the arrival time of the driver and his/her booking time. In addition, we calculate the difference between arrival and booking time per possible booking time. We see that early rides on average arrive after the booking time, while later rides on average arrive (well) before the booking time. From the boxplot, we conclude that there is much variation in the arrival of external carriers.

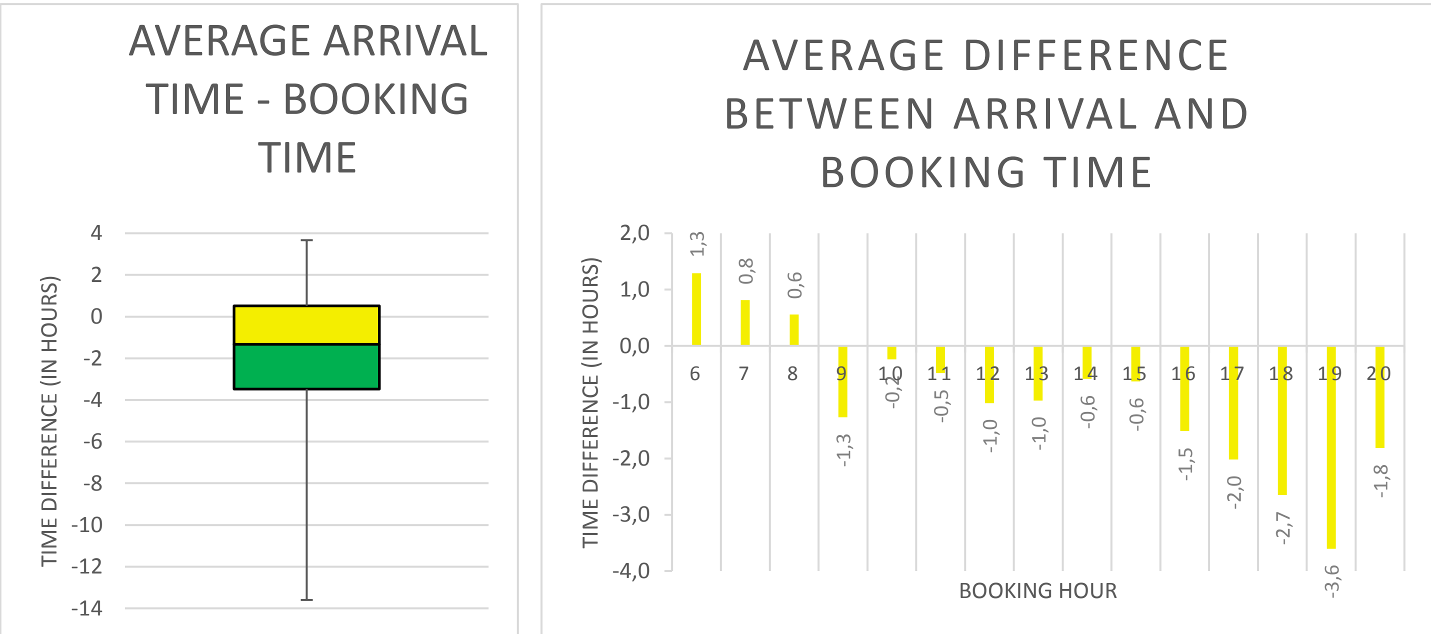

Figure 16: Deviation between arrival time and booking time

Because of uncertain arrivals, following the scheduling policy from figure 14 also has disadvantages. By continually keeping as many docks occupied as possible, the operation loses flexibility. It regularly happens that rides are waiting for a long time in the set-up outbound area, because the carrier is late. According to the WMS, on average 11.85 docks (out of 14 in total) are occupied during a working day. In practice, this number is even higher, because it takes the driver has to collect papers before leaving the dock. The system however sees the dock free as soon as the last pallet is loaded.

Rides wait on average 4 hours and 18 minutes at the set-up outbound area before they are loaded into a truck or container. This sounds worse than it is, since a lot of rides are being prepared the evening before they are picked up (i.e. rides are ready at 10 p.m. and are supposed to be picked up at 6 a.m.). Of the analyzed rides, 75% had no waiting time at the set-up outbound area due to lateness of the carrier. Only external carriers are taken into account in this analysis, rides for Carrier X and containers are irrelevant. The remaining rides averaged 88 minutes of waiting time at the set-up outbound area due to lateness of external carriers, see figure 17. The expected waiting due to lateness is thus 22 minutes.

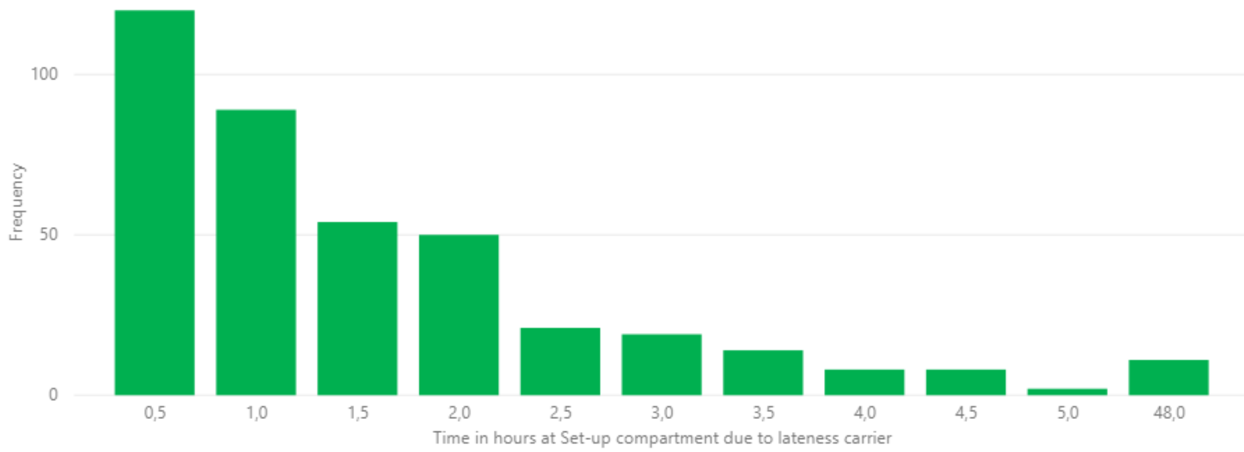

Figure 17: Time a ride has to wait in front of a dock due to lateness of external carrier

2.5 Workforce management

Internal logistics are performed by a number of warehouse workers. Each day is split up into three shifts: the early shift from 6 am till 2 pm, the late shift from 2 pm till 10 pm and the night shift from 10 pm till 6 am. During workdays, a full crew is available for the two dayshifts led by a team leader. Each night and during weekends, only one person (a team leader) is available. Transport from the Nouryon production site to the warehouse is done by shuttle truck drivers. One of the shuttle truck drivers is, just like a team leader, at all times available. Operational management is done by a desk employee and an operational planner, usually from 6 am till 4:30 pm. At other times, operational management is the task of the team leader. Lastly, there is a warehouse supervisor who is ultimately responsible and a variable number of support staff present. Figure 18 shows the staff of the warehouse, excluding all support staff.

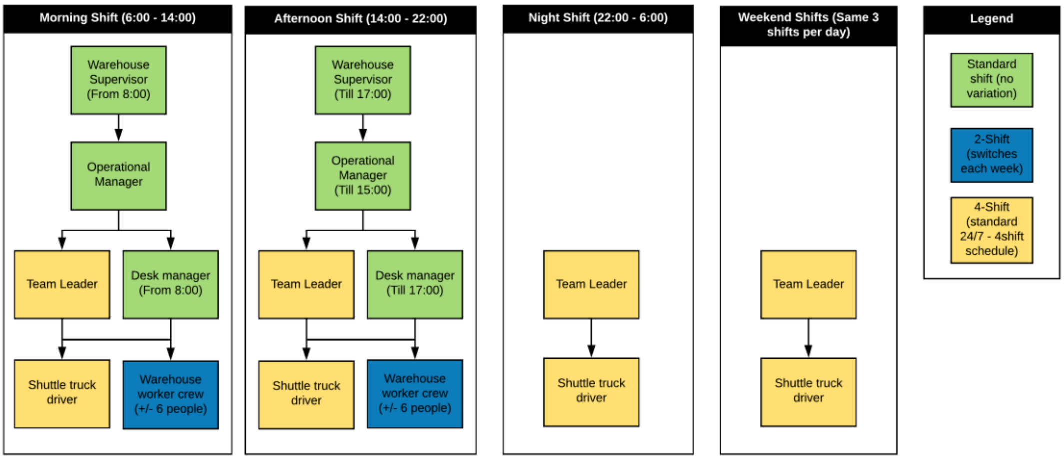

Figure 18: Schematical overview workforce at warehouse

On nights and weekends, the team leader and shuttle truck driver only handle inbound logistics, as no containers and trucks are loaded during these shifts. During dayshifts, team leaders act as a supervisor for the warehouse crew. Together they are responsible for the inbound logistics, as well as loading all rides. Each inbound pallet is, if nothing goes wrong, moved once on the day of inbound. Each outbound pallet is generally speaking moved twice, once towards the set-up outbound area and once into the truck or container. By calculating the total number of moved pallets during a shift, we can roughly measure the productivity. From figure 19, we see that the average number of actions performed per hour is roughly steady during the morning and afternoon shift (6:00 till 22:00). From 20:00 till 22:00, we see a small decline in performed actions. This can be explained by other duties that are performed in this timespan, such as cleaning and stock counting. From figure 20, we see that the type of performed actions differs during the day. In the morning pallets are mainly loaded into trucks and containers. In the evening pallets are moved internally, which could mean that they are moved to a set-up outbound area for an order of the next day or moved to another location to create space.

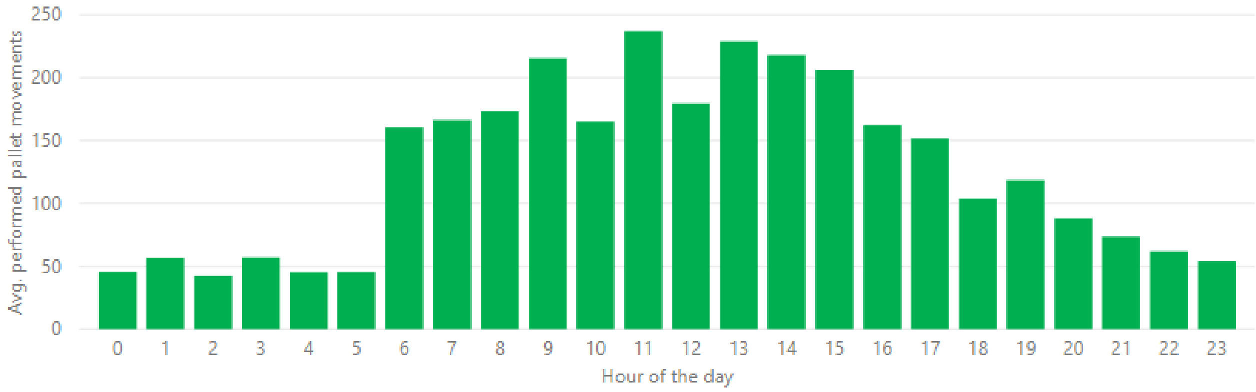

Figure 19: Total internal pallet movements per hour

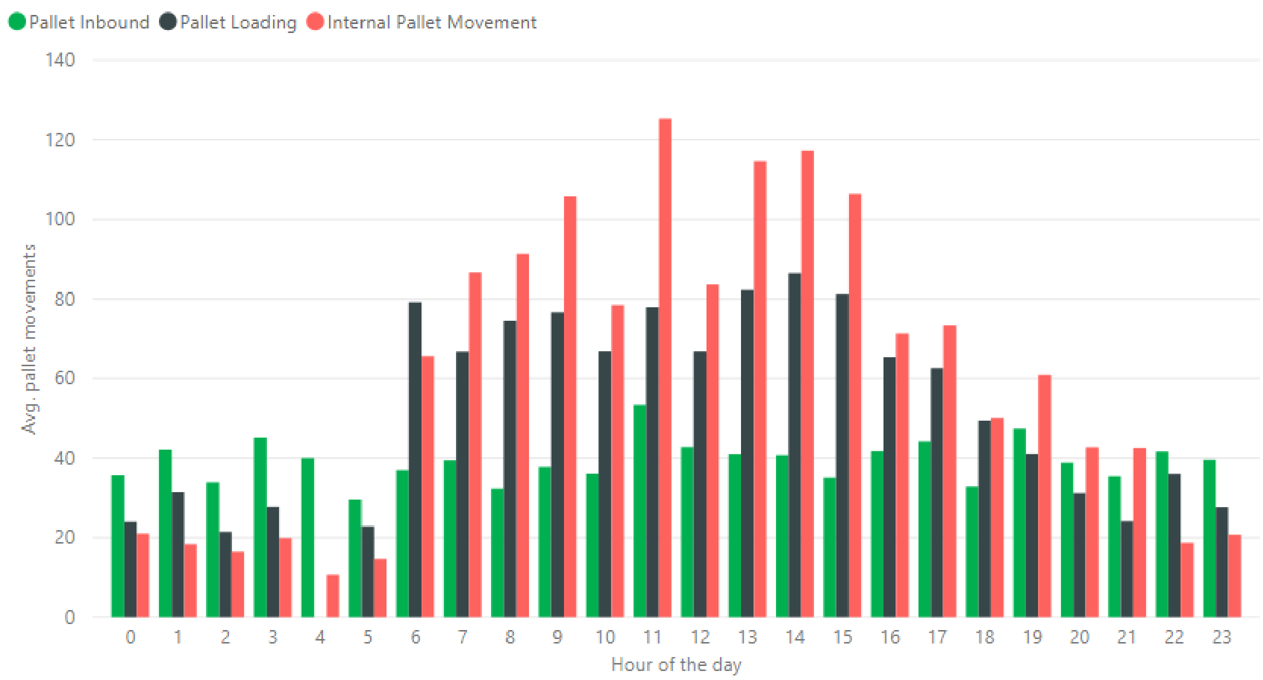

Figure 20: Internal pallet movements per category per hour

2.6 Conclusions

The field of warehousing was relatively unknown to Bolk Logistics at the start of the contract with Nouryon. As a result of this inexperience, logistical operations within the warehouse are not efficiently designed. At the time of our research, most of the larger inefficiencies are resolved. However, options for improvement are still easily found.

The first improvement detected is the storage decision for incoming pallets. Pallets are currently stored according to a class based policy with two classes: bulk storage and pallet racks. Within both classes, pallets are stored in the closest available location. This policy ensures all bulk storage locations close to the incoming goods point are utilized while storage locations in the back of the warehouse are left empty. However, fast-movers are often placed in the back of the warehouse, which results in long driving times. In Chapter 3, we consult literature for improvements in the storage heuristic and in Chapter 4, we propose a policy to improve the storage of products.

Secondly, the travel distance for order picking is high, since the dock for the outbound ride is chosen randomly by the operational management. It often occurs that warehouse workers have to travel a number of times from one side of the warehouse to the other side to complete an order. By choosing the right, closest, dock for the outbound ride, we can minimize the distance traveled. In Chapter 4, we calculate the theoretical improvement by complete enumeration.

The first two improvements are aimed at reducing the total distance traveled throughout the warehouse. The third and final improvement is aimed at levelling the workload throughout the day by improving the operational policy for releasing rides for picking. When workload peaks occur, the available capacity has to be able to deal with the workload. This means that more warehouse workers are needed during these peak hours. Management hopes that it is possible to decrease both dayshift teams by one person by leveling the workload. In chapter 5, we propose a number of policies for releasing rides for picking that are able to manage peaks in the workload.

3. Literature review

This chapter consults literature relevant to our research and it positions our research in a conceptual framework. In addition, similarities between literature and the problem Bolk Logistics is facing are discussed.

Section 3.1 classifies the warehouse of Bolk Logistics based on, among others, its warehouse function. Different storage methods are described in section 3.2. Lastly, section 3.3 explains a number of relevant optimization techniques.

3.1 Warehouse function

Warehouses are an essential component of any supply chain (Gu et al, 2006). A warehouse operation typically executes the following activities (Gu et al, 2006), (Richards, 2011):

1) Receiving: when receiving products at the warehouse, it is paramount to ensure that the correct product has been received in the right quantity. Thereafter, products are put away – often according to an allocation from a WMS – to a location in the warehouse.
2) Storage: the storage function of a warehouse can be split in three questions. Firstly, how much should be stored? Then, how should products be stored? Lastly, where in the warehouse should products be stored?
3) Order picking: order picking is the most costly activity in today's warehouses (Richards, 2011). It Is labor intensive, challenging to automate and difficult to plan.
4) Shipping: the shipping operation varies strongly between warehouses. Usually, it involves assignment of carriers to docks – which determines internal material flow – and allocation of material handling resources such as labor and material handling equipment (Gu et al, 2006).

To ensure all these processes are performed accurately, a warehouse management systems is often used (Min, 2007). According to Min (2007) the main benefits of a WMS are an increased order/inventory accuracy and value-adding services based on collected data.

Rouwenhorst et al. (2000) distinguishes between three levels in the design of warehouses: strategical, tactical and operational. Within each level, design problems can be defined.
Strategic decisions are long term decisions and have most of the time high investment costs. Decisions made at the strategical level are hard to change later on. Examples of decisions at the strategical level are:

- Space allocation for different activities: receiving, order picking, storage, shipping and an office.
- Storage methods: pallet racks (narrow isles or normal isles), bulk storage, automatic storage and retrieval system or a combination.

At the tactical level, decisions typically concern the dimensions of resources (storage system sizes but also number of employees) (Rouwenhorst et al, 2000). Problems at this level should be treated simultaneously, as they often influence each other. Examples are:

- Dimensioning of picking zones and selection of a storage concept (random, dedicated, class-based).
- Determining the number of warehouse staff workers
- Dimensioning of storage locations in the bulk storage.

Lastly, at the operational level, processes have to be carried out within the constraints set by the strategic and tactical decisions. Possible decisions at the operational level are:

- Assignment of personnel to activities (order picking, loading, receiving, etc.).
- Sequencing of incoming and outgoing rides.
- Assignment of trucks to docks.

There are many variations in warehouses. Warehouses can, among others, be subdivided based on warehouse type (Berg and Zijm, 1999), (Bartholdi and Hackman, 2016). Berg and Zijm (1999) differentiate between three warehouse functions: distribution, production and contract warehouses. In a distribution warehouse products are collected and send for delivery to customers. A production warehouse stores raw materials, semi-finished products and finished products from a production facility. A contract warehouse is a warehouse that performs the operation on behalf of customers. Bartholdi (2016) adds that companies often use a contracted warehouse – or a 3rd party logistics warehouse – to add value to their product.

Bolk Logistics Hengelo (mainly) performs logistical services for Nouryon. Bolk Logistics is thus the third party logistics warehouse for Nouryon. Bolk Logistics has no influence on the amount of product in their warehouse, but they are free to store products to their preference.
The four stages identified by Gu (2006) and Richards (2011) are still relevant, but some decisions are not influenceable by Bolk Logistics. Especially the scheduling of incoming and outgoing products is fixed by Nouryon. Both processes are unstable as well, which leads to challenges in the internal material flow.
With regards to Rouwenhorst's (2000) levels in warehouse design, a number of decisions are relevant. Receiving of products is done via shuttle truck and a conveyor belt (see section 2.2), which means that there is a strict distinction between receiving and loading docks. Since all products are sold per pallet, no colli picking is needed. Therefore, bulk storage with block stacking is the most efficient storage method. To increase capacity, a narrow aisle pallet rack system is used.
Per product a choice between pallet rack and bulk storage is made. Within the bulk storage and pallet rack system products are stored randomly. Since the start of the operation for Nouryon in September 2018, Bolk Logistics is trying to decrease the number of fixed warehouse staff members by increasing efficiency.
Since scheduling of incoming and outgoing products is managed by Nouryon, it is hard to influence the internal material flow within the warehouse. One of the only possibilities to influence the material flow is by releasing rides for picking at the right moment at the right loading dock.

3.2 Storage methods

As mentioned in the section above, storage methods can be divided into three groups: random, dedicated and class-based. In this section, we discuss each of the groups and explore which methods are useful for Bolk Logistics

3.2.1 Random storage

Random storage means that items are randomly stored in a location. Its advantages are the uniform utilization of the warehouse and reduced aisle congestion. As a result, it requires less space than other storage methods. Its main disadvantage is the possibility of large travel times (Petersen, 1999).

3.2.2 Dedicated storage

The opposite of random storage is dedicated storage where each stock keeping unit (SKU) has its own fixed location within the warehouse. It is based on the idea that fast-moving items should be located in easily accessible areas. A lot of dedicated storing policies can be found in literature. Among those are the are the cube per order index (COI) (Kallina and Lynn, 1976) and order oriented slotting (OOS) (Mantel, Schuur and Heragu, 2007).

The cube per order index (COI) allocates storage space to inventory items in a warehouse based on the ratio of the storage requirement for an item to its popularity. COI based storage means assigning items with a low ratio of the required storage space to the order frequency to the locations nearest to the I/O point. The follow variables are used for the COI:

m = number of input/output points
S_j = number of storage locations required for SKU j
T_j = number of trips for SKU j (= throughput)
p_i = percentage of travel to I/O point i
d_{ik} = distance from I/O point i to storage location k

The COI first ranks all locations based on distance to the I/O points with:

$$f_k = \sum_{i=1}^{m} p_i d_{i,k}$$

Here the lowest f_k is the best location. Then, items are ranked based on their cube per order index:

$$COI_j = \frac{T_j}{S_j}$$

Here the highest COI_j is the most important item. This item is then stored in the best location as calculated above (Heskett, 1963).

The order oriented slotting strategy (OOS) (Mantel, Schuur and Heragu, 2007) takes, in contrast with the cube per order index, the correlation between products into account. Some products are often ordered together and it might be beneficial to store these items close to each other. Order oriented slotting is mostly interesting when an order picker picks multiple items in one trip. For a medium small warehouse, the OOS strategy can be solved to optimality with linear programming (Mantel et al. 2007) .

To incorporate the interaction between products, the authors use two variables:

f_{i0} = number of orders that require product i
f_{ij} = number of orders that require product i and product j

The authors also give a comparison between COI and OOS, see figure 21. Note that in this case, the OOS performs better. This is however a simplified example, as all orders are disjoint.

Figure 21: Comparison between COI and OOS in a numerical example (Mantel, Schuur and Heragu, 2007)

3.2.3 Class based storage

Class based storage is a mix between random storage and dedicated storage as it partitions SKUs into storage classes and randomly assigns storage locations within each storage class area (Petersen, Aase, Heiser, 2004). Assigning products to a storage class is done based on their turnover (Van den Berg, 1996). The goal of a class based storage policy is to minimize the mean single command cycle time (Hausman et al, 1976). In a single command cycle either one storage or retrieval is performed.

Class based storage can be used with most of the dedicated storage policies. For example, OOS could be used to assign products to a certain class. Within this class, location assignment will then be random.

3.2.4 Situation at Bolk Logistics

Bolk Logistics currently uses a class based storage policy with 2 classes (block stacking in bulk and pallet racks). Products are placed in the pallet racks based on turnover speed. Within both the zones (bulk storage and pallet racks) products are assigned randomly. After our current situation analysis, we believe this results in unnecessary high driving distances within the warehouse.

Dedicated storage is no option for the logistical services for Nouryon, since the products that are present differ strongly. There are approximately 250 bulk storage locations and 100 products which are stored in the bulk. However, most of these products require multiple storage locations per batch. It is thus impossible to reserve locations in the bulk storage zone for each product. Reserving locations for a number of products pooled together does belong to the possibilities. This would lead to extra storage classes within the bulk storage zone.

There is not one single method found in literature that is able to classify products into storage classes for Bolk Logistics. Order oriented slotting (Mantel, Schuur and Heragu, 2007) is unable to cope with the material flow as it assumes multiple items are picked up within one trip. At Bolk Logistics, a fork truck is only able to transport two pallets of one product in one trip. A cube per order index (Heskett, 1963) is not suitable either, as it does not incorporate the interaction between products that are often ordered together. Even though only one product at the same time is transported at Bolk Logistics, this interaction is still relevant for the choice for outbound loading dock. Each of the fourteen loading docks at Bolk Logistics can be used. If all products for an order are located near each other, the distance to the closest dock is smaller than when all products are scattered throughout the warehouse.
Ideally, a suitable storage policy takes into account:

- Turnover of a product
- Interaction between different products
- Assignment of outbound loading dock

3.3 Optimization techniques

Many optimization techniques are described in literature. This section describes mathematical models, approximation algorithms and simulation models.

3.3.1 Mathematical models: Integer programming

An integer linear programming model is a mathematical model that describes problems in terms of linear relationships. A binary integer programming (BIP) model is a integer programming model that uses only binary variables. Many practical problems in operations research can be expressed as linear programming problems (Garey and Johnson, 1979). The main advantage of a BIP is that it evaluates the complete solution space, i.e. each possibility is considered. This ensures that the found solution is the optimal solution. A disadvantage of this method is the inability to solve (very) large problems.

A binary integer programming model consists of:

- Objective function: a function that should either be minimized or maximized depending on the problem.
- Binary decision variables: decisions that influence the objective function.
- Problem constraints: constraints that limit the values of decision variables.

3.3.2 Approximation algorithms: Simulated annealing

Approximation algorithms, or heuristics, are used to evaluate large problems systematically. Heuristics are therefore able to find good solutions, even for NP-hard problems, in polynomial time. In literature many algorithms can be found. One of the most popular heuristics is Simulated Annealing (SA). One of the main advantages of SA is that is able to escape from local optima.

The algorithm is based on statistical mechanics (the behavior of systems with many degrees of freedom in thermal equilibrium at a finite temperature) (Kirkpatrick, Gelatt, & Vecchi, 1983). This is still visible in the algorithm as the temperature of the algorithm plays an important part.

The algorithm starts with a starting solution and a starting temperature (C_{start}). The initial starting solution has a strong influence on the performance of the algorithm (De-Souza et al., 2009). Then a new neighbor solution is created and evaluated. The result of the new solution (B) is compared to the current solution (A) with the following formula in case of a minimization problem:

$$P(c)\begin{cases} 1 & if\ B\ \leq A \\ e^{\frac{A-B}{c}} & otherwise \end{cases}$$

Here $P(c)$ is the probability that a transition from the current solution (A) to the new solution (B) is accepted. It can be seen that a better solution is always accepted, whereas the acceptance of worse solutions is dependent on the current temperature. After k iterations, the temperature c is decreased with decreasing factor α. The lower the temperature, the less likely it is that a worse solution is accepted.

The algorithm can be summarized in pseudo code:

$c_{current} = c_{start}$
$Set\ starting\ solution\ S_{start}$
$S_{best} = S_{start}$
while $c_{current} > c_{stop}$
  for $i = 1\ to\ k$
    $S_{neighbor} = getNeighbor(S_{current})$
    if $exp\frac{\max(f(S_{current})-f(S_{neighbor})),0)}{c_{current}} > randbeteween(0,1)$
      if $f(S_{neighbor)} \leq f(S_{best})$
        $S_{best} = S_{current}$
      $S_{current} = S_{neighbor}$
  $c_{current} = c_{current} * \alpha$

The neighbor solution does not always have to be generated in order to evaluate its objective value, $f(S_{neighbor})$. The objective value can, for most problems, be calculated without evaluating the entire solution.

The cooling scheme for a simulated annealing algorithm is paramount for its performance. When choosing the starting temperature or decreasing factor too high, or the end temperature too low, the running time of the algorithm will quickly increase. There are however no strict rules about the choice of C_{start}, C_{stop}, α and k. One rule of thumb is that the acceptance ratio during the starting temperature should be close to 1. This means that almost all proposed neighbors should be accepted to ensure the entire solution space is reachable. The acceptance ratio can be calculated with:

$$Acceptance\ ratio = \frac{Number\ of\ acceptanced\ transitions\ during\ starting\ temperature}{Number\ of\ proposed\ transitions\ during\ starting\ temperature}$$

3.3.3 Simulation models

New policies can be tested in the real system, but it will take a long time before significant data is collected. Therefore simulation models are often used to test policies for a complex system for which it is impossible to analytically analyze the system. Simulation is however a time costly process which requires a lot of input data (Robinson, 2014).

A simulation is a approximate imitation of the operation of a process or system (Banks et al., 1996). By changing variables in the simulation, predictions can be made about the behavior of the system. To ensure that the predictions are valid, it is important to validate and verify the simulation model.

3.3.4 Optimization techniques in this research

To find an optimal storage allocation for all products to the new storage zones, we first try an integer programming model. The number of variables however proved to be too high for the software, which means that the storage allocation cannot be solved with a BIP. Therefore, we simplify the BIP. The solution of the simplified solution can then be used as upper bound for a Simulated Annealing algorithm. Chapter 4 will explain this journey in more detail.

To find an improved scheduling policy for releasing rides for picking, we use a simulation model. This simulation model encompasses the outbound logistics of the logistical services for Nouryon. With this simulation model, we evaluate the performance of eight different policies. Chapters 5 and 6 contain respectively the definition of the policies and the simulation study itself.

4. Lowering the total workload

From Chapter 2 current situation, we conclude that we have to decrease waste of man hours, and thus indirectly personnel costs on the warehouse floor. The current situation analysis proposes two improvements: an improved picking policy and better storage decisions for incoming pallets. This chapter will discuss both improvements in detail. First, a new tactical storage policy for incoming products in the bulk storage locations is proposed. Products will be stored smarter within the warehouse by taking demand, average inventory and popular product combinations within orders into account. Secondly, order picking distance is minimized by advising a loading dock in real time. By combining tactical and operational improvements, we are able to reduce the total workload at the work floor.

Section 4.1 describes the idea behind the new storage policy. A binary integer programming (BIP) model is constructed to solve the storage assignment of products in section 4.2. Section 4.3 simplifies the BIP model by relaxation of the interaction constraint, while section 4.4 attempts to solve the storage assignment problem with a Simulated Annealing (SA) algorithm. Section 4.5 introduces the new loading dock choice policy. Results of all models are discussed in section 4.6.

4.1 Assigning products to a storage zone

In the current situation, see section 2.2 inbound logistics, the bulk storage location for a new batch is chosen based on minimum driving distance from the receiving area (conveyor belt at docks 25 and 26). As a result, different batches from the same product are scattered around the warehouse and fast-movers are often located in the back of the warehouse. Assigning each product to a number of bulk storage locations, i.e. dedicated storage, is unfeasible for Bolk Logistics, because products do not have stable inventory quantities. If each product has a fixed location, the warehouse needs to be a lot bigger and storage space will often be wasted.

We propose a mixed storage method by combining dedicated and random storage into a class based storage policy. Bulk storage locations are divided into ten zones, see figure 22. Each of the hundred products that are stored in bulk storage is assigned to one of these ten zones (= dedicated). Within each zone storage decisions are based on minimal driving distance from the receiving area (= semi random), similarly to the current situation. The main constraint is that the average inventory of all products within a zone cannot exceed the capacity of the zone. By storing multiple products in a zone, the total number of storage locations needed within that zone is steadier than when each product has a dedicated location. This is due to the risk pooling principle: high inventory for one product is offset by low inventory for another product.

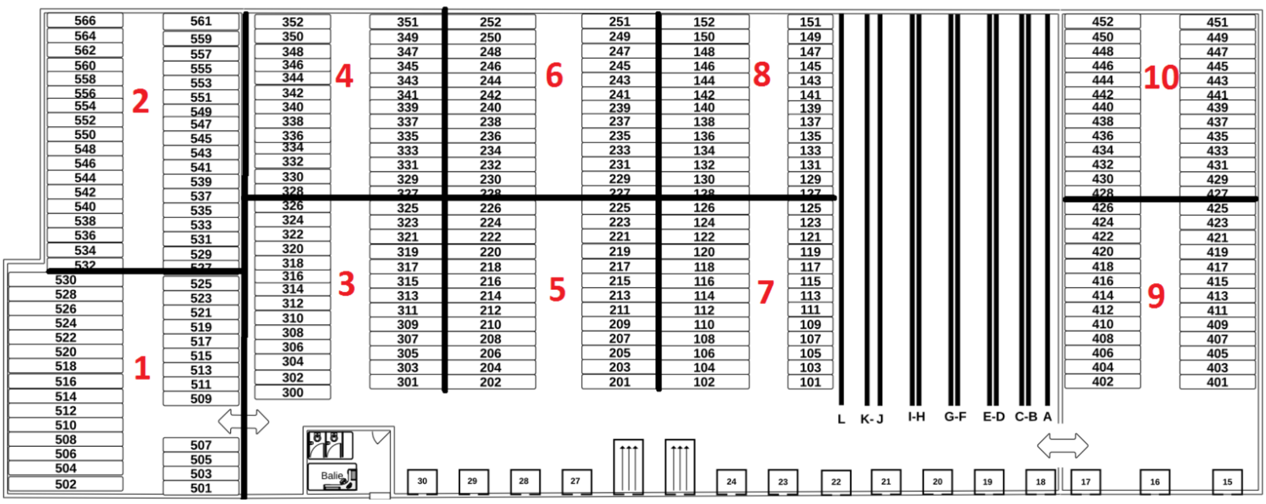

Figure 22: Division of bulk storage zones

When designing a storage strategy, we have to account for correlation between products. Some products are often loaded together with another product. As a result, these products have to be transported to the same loading dock and it is thus interesting to place the products in the same zone. The actual driving distance between the two products is irrelevant, because a forklift driver is unable to transport two different products at the same time due to software restrictions. The forklift drivers are however able to transport 2 pallets of the same product at the same time.

4.2 BIP model description

To solve the storage assignment problem optimally, we formulate a binary integer programming (BIP) model. An BIP consists of an objective function, binary decision variables and constraints. These three components are explained in this section. Afterwards, the mathematical notation of the BIP is given and results are discussed.

4.2.1 Objective function

The objective of the storage allocation problem is to minimize the total travel distance within the warehouse. The total travel distance is defined as the sum of the distance to store all products and the distance to pick all products. Replenishment movements within the warehouse are not taken into account.

In order to minimize travel distance, it is paramount to store fast-movers in the front of the warehouse. If all orders would be full truckloads of a single product, this allocation would be optimal. However, over 40 percent of all trucks contain multiple products. This correlation changes the optimal allocation, because it is beneficial to store products that are often loaded together close to each other. For example, lets envision order O with 12 pallets of product A and 8 pallets of product B. Assume product A is stored in zone 3 from figure 22 and that product B is stored in zone 9. In this case, the dock which minimizes travel distance is dock 30 with an expected travel distance of 2.83 kilometers. If we now replace product B from zone 9 to zone 7, the dock which minimizes travel distance is still dock 30 (see figure 22). The expected travel distance, however, has decreased with 27% to 2.06 kilometers.

Recall that the actual driving distance between the products is irrelevant, since the order picker only transports one product at a time. The correlation between products i and j is modeled by calculating the number of pallets of product i that are loaded together with product j. So, if this correlation value equals n, it means that n pallets of product i are loaded together with - an unknown number of pallets of - product j. See figure 23 below, here $DemandCor_{AA} = 16$, $DemandCor_{AB} = 10$, $DemandCor_{BA} = 8$ and $DemandCor_{BB} = 0$.

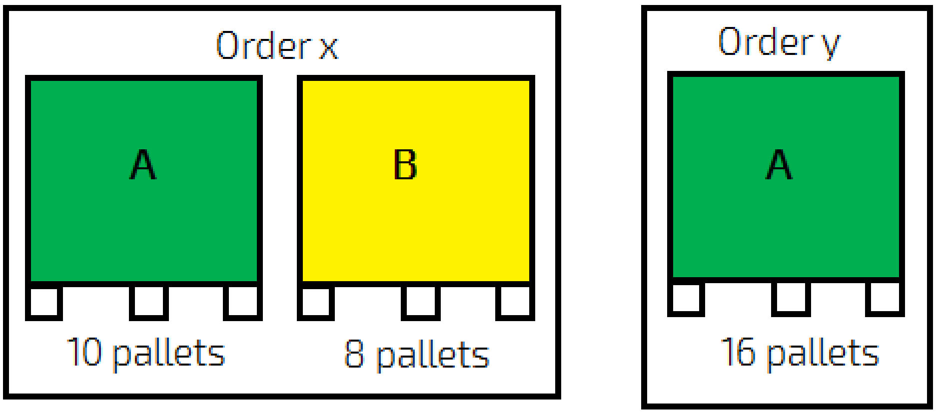

Figure 23: Explanation demand correlation in BIP

4.2.2 Decision variables

The main decision is the allocation of products to a storage zone, i.e. where to store each product. A result of the storage decisions is the decision on which of the fourteen docks products are loaded. For each combination of two products (i and j) the nearest dock (d) is chosen based on the correlation between the two products. The correlation between three products is not taken into account. See section 4.4.1 Assumptions for an explanation. In reality, the decision where to load a set of products is easily made based on minimal driving distance. In the model however, this calculation is not possible and as a result the dock choice is included as a decision variable.

4.2.3 BIP model

The mathematical model is divided into sets, parameters, decisions, constraints and an objective.

Indices of sets

i, j	Products that need to be stored in bulk storage (1-100)
z	Zones where products can be stored (1-10)
d	Docks where orders can be loaded (1-14)

Parameters

$LocProd_{i,z}$	Number of locations needed to store product i in zone z
$CapLoc_z$	Number of locations in storage zone z
$DistDock_{z,d}$	Distance from (the middle of) zone z to dock d
$DistReceive_z$	Distance from the receiving area to zone z
$DemandCor_{i,j}$	Number of pallets from product i loaded together with product j

Decision variables

$X_{i,z}$	1 if product i is stored in zone z, 0 otherwise
$Y_{i,j,d}$	1 if product i is loaded together with product j at dock d, 0 otherwise
$Product_{i,j,z,d}$	The product of $X_{i,z}$ and $Y_{i,j,d}$ (see decisions), computed with constraints to ensure linearity. It equals 1 if and only if product i is stored in zone z and loaded together with product j at dock d.

Objective function

Minimize:

$$\sum_i \sum_j \sum_z DemandCor_{i,j}(X_{i,z} * DistReceive_z + \sum_d Product_{i,j,z,d} * DistDock_{z,d})$$

Constraints

$$\sum_z X_{i,z} = 1 \;\; \forall\, i \qquad (1)$$

$$\sum_d Y_{i,j,d} = 1 \;\; \forall\, i, j \qquad (2)$$

$$\sum_i (X_{i,z} * LocProd_{i,z}) \;\leq CapLoc_z \;\;\; \forall\, z \qquad (3)$$

$$Y_{i,j,d} = Y_{j,i,d} \;\; \forall\, i, j, d \qquad (4)$$

$$Product_{i,j,z,d} \geq X_{i,z} + Y_{i,j,d} - 1 \;\; \forall\, i, j, z, d \qquad (5)$$

$$X_{i,z}, Y_{i,j,d}, Product_{i,j,z,d}\ \{0,1\} \;\; \forall\, i, j, z, d \qquad (6)$$

Constraint (1) ensures that every product is stored in one of the storage zones. Constraint (2) ensures that each pair of products is loaded on a dock. It ensures each pair of products has to select one dock on which these products are loaded. This dock choice only has influence on the objective function if their $DemandCor$ is larger than 0. Thanks to constraint (4), the loading dock of product i with product j is symmetrical, which means that it is the same as the loading dock of product j with product i. The capacity of each storage zone is not exceeded because of constraint (3). Constraint (5) takes care of the non-linearity of a product of two decision variables, multiplying $X_{i,z}$ and $Y_{i,j,d}$ would mean that the model loses its linearity. Constraint (5) ensures that $Product_{i,j,z,d}$ equals 1 if both $X_{i,z}$ and $Y_{i,j,d}$ are 1. Whenever one of them is not 1, $Product_{i,j,z,d}$ can be either 0 or 1 ($Product_{i,j,z,d}$ is a binary variable thanks to constraint (6)). Because $Product_{i,j,z,d}$ is part of the objective function and the objective function is a minimization, $Product_{i,j,z,d}$ will always be 0 if it can choose between 0 and 1.

4.2.4 Results

We model the BIP above in an open source software program specifically designed for solving BIP problems, named lp_solve (lpsolve.net, 2019). Since there are 100 products, 10 zones and 14 docks, $Product_{i,j,z,d}$ has a dimension of 1.4 million. This means that the software program has to evaluate over 1.4 million binary variables. The software program turned out to be unable to handle this amount of variables, so we are unable to solve the storage assignment problem to optimality with the BIP.

After some trial and error, we found that the software program was able to find the optimal solution up till 8 different products. One possible way to solve the assignment problem would thus be to group all products together into 8 clusters and then solve the BIP for these eight clusters. Products within a cluster should have a lot of correlation, whereas products from different clusters should have minimal correlation. After some initial calculations, we found that it is difficult to group products together in eight clusters with minimal correlation between clusters. Therefore, we discard the option of clustering before solving the BIP.

4.3 Simplifying the BIP model

We decide to simplify the BIP model from section 4.2 by removing the correlation between products. We now assume that products are always loaded without other products. In other words, each truckload / container only consists of pallets of one product. As a result, the storage assignment problem can be solved to optimality by the Cube per Order Index (COI) strategy with a capacity constraint as discussed in section 3.2.4.

Thanks to this assumption, the BIP becomes manageable for the software program. As can be seen in the formulation of the BIP in Appendix A, the only decision variable left is where to store each product ($X_{i,z}$). The decision where to load each order is no longer relevant, since it solely depends on where each product is stored. When the location of a product is known, the closest dock is easily found. We calculated the average total distance travelled for each pallet per storage zone by adding the distance from the receiving area to the storage zone and the distance from the closest dock to the storage zone.

The output of the simplified BIP model assigns each product to a storage zone, see Appendix A. If no correlation between products would exists, this solution would be optimal. Unfortunately, about 40% of all orders consist of multiple products. For example, n pallets of product 'X' are loaded together with product 'Y' during June 2019. This combination alone accounts for approximately 2% of all loaded pallets. The first product is placed in zone 8 by the BIP, while the latter is placed in zone 1. As can be seen in figure 22, the products are placed far from each other which leads to unnecessary long driving distances for towards the outbound loading dock.

We expect that we are able to decrease the total driving distance further by accounting for the correlation between products. Therefore, we have to use a heuristic to find a solution for the assignment problem with correlated products.

4.4 Heuristic for BIP with product correlation

This section discusses the implementation of a Simulated Annealing Heuristic for solving the storage assignment problem with correlated products. The heuristic is implemented in Java. In this section we successively discuss: assumptions made, the objective function, neighbor solution creation, cooling parameters and the results of the heuristic.

4.4.1 Assumptions

Before explaining the algorithm, we specify the assumptions and choices made.

The main assumption is the restriction to two-dimensional correlation between products. Just as in the BIP, we assume that an order never contains more than two different products. If we would take a third product into account, we would have to calculate the demand for all combinations of three products. This would significantly impact the size of the problem. Including the fourth and fifth dimension as well would make calculations impossible. As a compromise, we calculate for every product in an order how much pallets are loaded together with the most common product in that order. To illustrate, see the three orders in figure 24. Here $Demand_{A,A} = 16, Demand_{A,B} = 18, Demand_{A,C} = 0, Demand_{B,A} = 12, Demand_{B,B} = 0, Demand_{B,C} = 0, Demand_{C,A} = 2, Demand_{C,B} = 0$ and $Demand_{C,C} = 0$. Each pair of products is loaded at a fixed dock ($Dock_{A,B} = Dock_{B,A}$). A benefit of this method is that the total demand of a product is easily calculated by summing over the product (i.e. 34 pallets for product A). A disbenefit from this assumption is that it could happen that products A and B together are loaded at a different dock than products A and C. In the model, pallets from order x would thus be loaded at two different docks. However, less than 20% of all orders contain more than 2 products and the inaccuracy in driving distance is small.

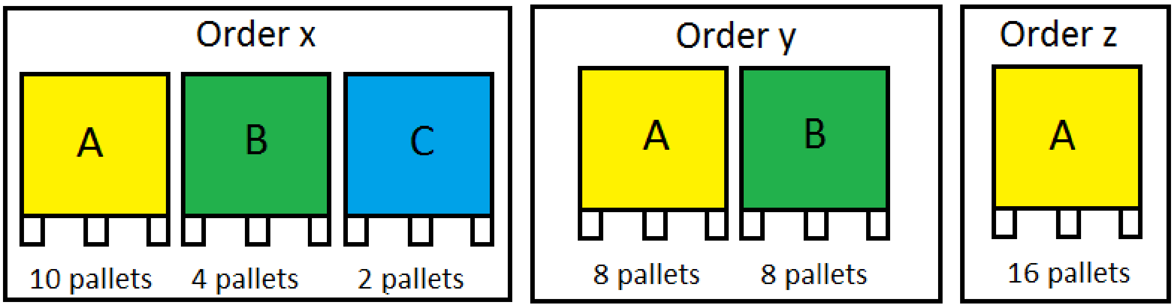

Figure 24: Explanation demand correlation assumption for multiple products

Furthermore, we do not include movements within the warehouse in the total distance. Only the distance traveled to store the product and the distance traveled to the set-up outbound area are taken into consideration. Replenishment movements, for example, are not included.

Lastly, we assume that each product has a constant inventory level which is equal to the actual average inventory level. Based on the inventory, we calculate the number of storage locations needed to store the product. Combined with the storage decision per product, capacity violations can be calculated. In reality, the number of required storage locations is not constant, which means that products sometimes have to be stored in another storage zone. This effect could be reduced by lowering the total number of zones, as the risk pooling effect will decrease the variation in number of products within a zone when more products are stored within a zone.

4.4.2 Objective function

The performance of each solution is evaluated by an objective function. Minimizing this objective function approaches an optimal solution. The objective of the algorithm is to find a storage allocation for all products that minimizes driving distance within the warehouse. The objective function thus has to be focused on the total driving distance.

In addition, capacity constraints are relaxed compared to the BIP models. Capacity can be violated in the algorithm, but a violation leads to a penalty in the objective function. By allowing capacity to be violated, the algorithm does not get stuck on a local optimum, but is able to search the entire solution space. Capacity violations are punished by increasing the total distance by a certain percentage (1 percentage point per 1 capacity violation).

The objective function that should be minimized is:

$$Objective = Total\ driving\ distance * (1 + Capacity\ Violation * 0.01)$$

Where the capacity violation is the sum of the capacity violation for all storage zones.

4.4.3 Creating neighbor solutions

The entire solution space should be accessible by creating neighbors in a simulated annealing algorithm. There are a number of methods available for creating neighbors. In our research, the MOVE and SWAP operator are used.

The SWAP operator swaps the storage assignment of two random products as long as the products are stored in a different storage zone. Before and after swapping the products, the objective function is calculated. The MOVE operators moves one random product to another random storage zone. Before and after moving the product, the objective function is calculated. If the new objective value is lower than the old objective value, the swap or move is accepted. If the new objective value is higher, the probability of acceptance is dependent on the current temperature of the algorithm (see section 3.3.2). If the swap or move is not accepted, products are assigned back to their original storage zone. See figure 25 for a flowchart of the creation of neighbor solutions.

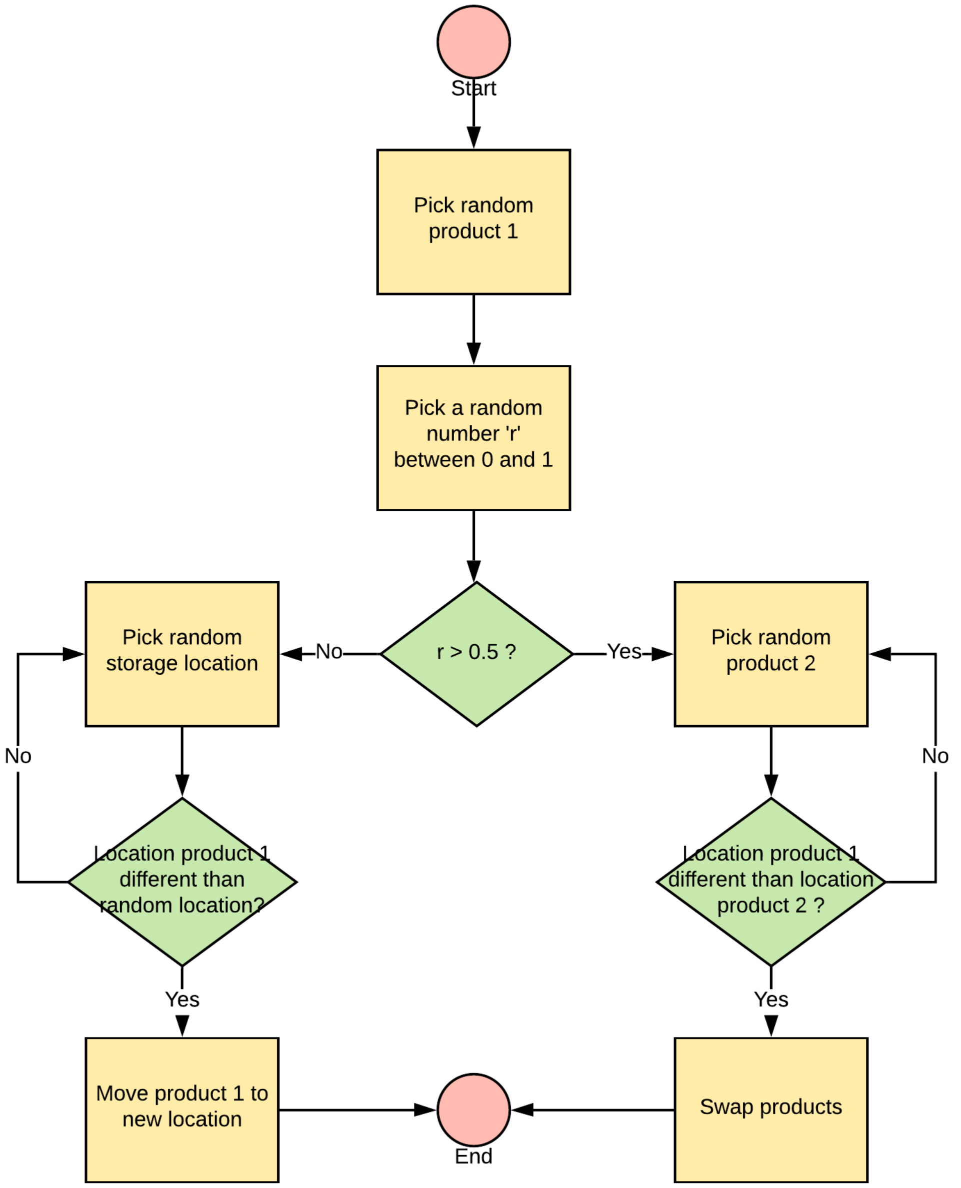

Figure 25: Neighborhood solution creation in Simulated Annealing algorithm

Recall from literature (section 3.3.2) that a starting solution has influence on the performance of a SA algorithm. We tried three different methods for generating starting solutions: the optimal solution from the simplified BIP model, a completely random solution and a feasible random solution. We found that the latter performed the best.

4.4.4 Cooling parameters

In section 3.3.2 we discussed the importance of a fitting cooling scheme for a simulated annealing algorithm. A cooling scheme for simulated annealing consists of a starting temperature, a stop temperature, a decrease factor for the temperature and the amount of iterations performed per temperature.

The starting temperature should be chosen such that the acceptance ratio at the starting temperature is close to 1. The acceptance ratio is the percentage of proposed neighbor solutions that is accepted. We calculated the acceptance percentage for a number of different starting temperatures, see figure 26. From this we conclude that a starting temperature of 1.5 million is sufficient as the acceptance ratio is above 95%.

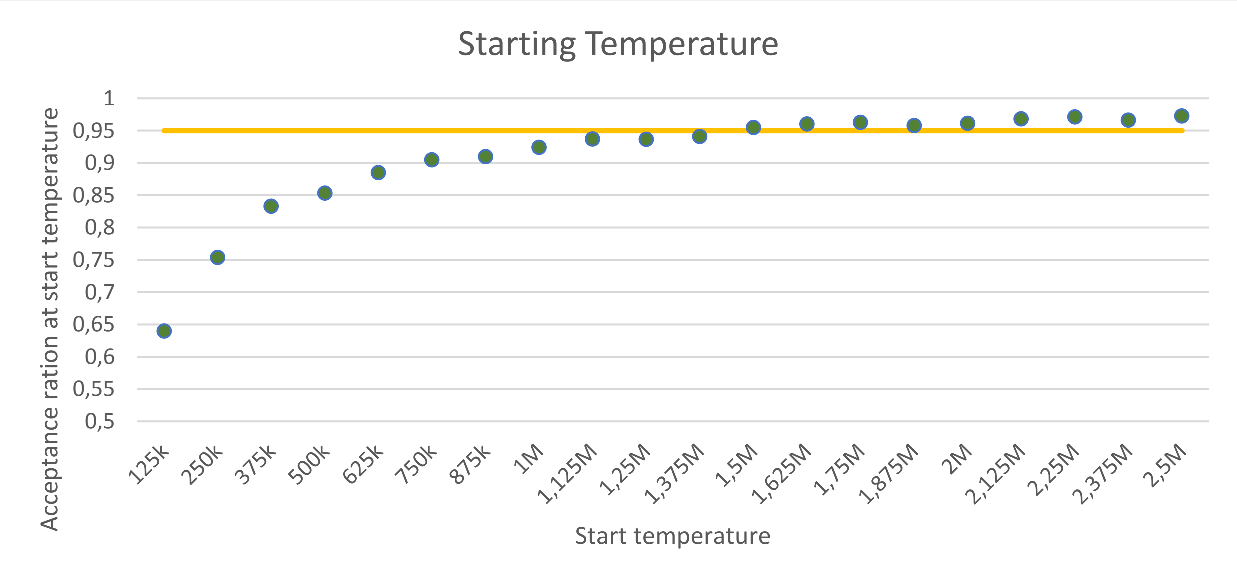

Figure 26: Determining starting temperature SA algorithm

The ending temperature should be chosen such that the acceptance ratio at the ending temperature is close to 0. From figure 27, we conclude that 5 thousand is an acceptable end temperature, as the acceptance ratio is below 1% for the first time at this point.

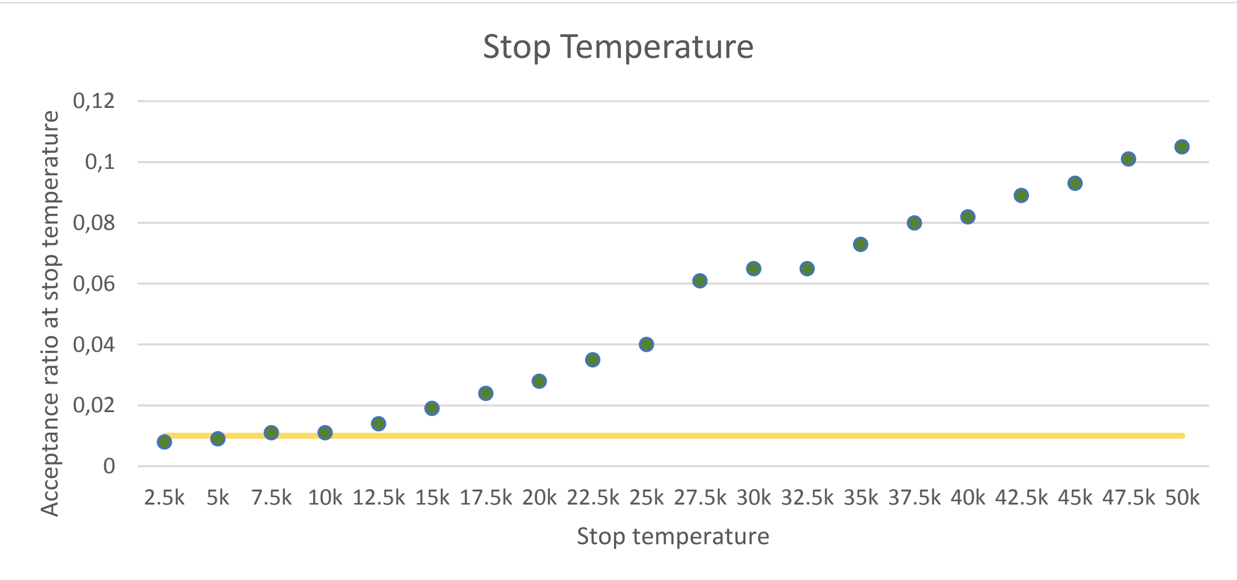

Figure 27: Determining stop temperature SA algorithm

We choose the decreasing factor and the number of iterations such that the algorithm has time to find the optimal value while the running time does not get too long. After some initial test runs, we set the decreasing factor to 0.99 and the number of iterations to 250.

4.4.5 Results

The simulated annealing algorithm tries to minimize the total driving distance by changing storage assignments for products. The result of the simulated annealing algorithm is thus the storage assignment with the best objective value found. After running the algorithm a number of times, the best assignment found was selected. This assignment can be seen in Appendix B.

Compared to the assignment from the simplified BIP model, the product allocation assignment resulting from the SA algorithm differs for a lot of products. It does however stand out that products that are stored in the front of the warehouse (uneven zones) in the BIP model are also stored in the front by the SA algorithm. The correlation between products is probably responsible for the differences in storage assignment. The objective values of all different storage assignment methods are discussed in section 4.6.

4.5 Order picking: Choice of loading dock

In the previous sections, we developed methods to assign products to a storage zone. In addition to the storage assignment, the choice for an outbound loading dock affects the picking time for warehouse workers strongly as was underlined in section 2.3. Currently the operational manager or desk employee chooses the loading dock randomly.

Improving the loading dock decision is mathematically easy. Since it is known where products are stored, the closest loading dock can be calculated by total enumeration. There are only fourteen loading docks, which means that the calculation time for total enumeration is low. The challenge for the dock decision lies however in the implementation.

As opposed to the storage assignment problem, the decision for a loading dock is made operationally. This means that the decision depends on the current state of the warehouse, instead of an average state of the warehouse (as for the storage assignment problem). The decision could be made by the warehouse management system (WMS) at the moment a ride/order is released for picking, but the costs for developing this feature are high. In addition, the WMS matches pallets to an order at the moment an order is released for picking. The WMS does not know beforehand which pallets are for which order.

To provide more information, we constructed a planning assistance application, see Appendix G.1.. This application connects products to orders according to the same criteria as the WMS and is thus able to estimate which pallets are allocated to which order. Based on this allocation, the application calculates the nearest loading dock as well as the location of the products for every order of the day. However, if the schedule or if orders are changed, the estimation of the application can differ from the WMS. Therefore, the application is updated hourly.

4.6 Results

In this chapter, we evaluated six scenarios to decrease the total driving distance within the warehouse:

1. No smart storage & random dock choice (= current situation)
2. No smart storage & nearest dock choice (= planning assistance application)
3. Storage assignment without correlation between products & random dock choice (= simplified BIP)
4. Storage assignment without correlation between products & nearest dock choice (= simplified BIP and planning assistance application)
5. Storage assignment with correlation between products & random dock choice (= simulated annealing algorithm)
6. Storage assignment with correlation between products & nearest dock choice (= simulated annealing algorithm and planning assistance application)

For each of the six scenarios, we compute the total expected driving distance for all orders from the last three months. Scenario 1 is seen as the base scenario and is indexed with index 100. The other scenarios are compared to the base scenario. See table 2 for the results.

Table 2: Indexed results storage assignment and dock allocation

Scenario	1	2	3	4	5	6
Index	100	80,6	88,3	68,2	87,5	67,4

When looking at table 2, we first notice that the improved dock policy has more impact on the driving distance than the improved storage assignment decision. Yet, the best results are achieved when both policies are combined. Secondly, it stands out that the differences in objective value between the BIP model and the SA algorithm are negligible. It thus has little use to account for correlation between products when assigning products to storage zones, as the SA algorithm is more complicated than BIP.

Theoretically, we are able to reduce the total driving distance within the warehouse with 32.5% by implementing the two proposed improvements. According to management, approximately two-thirds of the working time is spent driving. This implies that our improvements could cut the total workload of warehouse workers by more than 20%.

However, this improvement is only in theory. In our models, we assume that products always fit within their destined zone. Products are allocated to a zone based on their average storage needs. By combining multiple products within a zone, the variation of total storage needs within a zone is decreased due to risk pooling. However, it will still occur that a zone has no empty storage locations left. The product then has to be stored in another storage zone. This would lead to extra driving distance. Another assumption in our models is that loading docks are always free. In reality, a number of loading docks are always occupied. It is then not possible to release an order or ride at this loading dock, which means that another – suboptimal - loading dock has to be chosen. At the moment, on average 11.8 docks are occupied during the day, leaving only 2.2 docks free to choose from. This means that the improvements of dock choice are minimal in the current situation. To further increase the savings, we will improve the scheduling of the outbound logistics in chapters 5 and 6.

In addition to the reduction in driving distance, there are other benefits to the new policies. One of the main improvements lies in the replenishment of products. When bulk storage locations are underutilized, products are moved to another location with the same product or towards the pallet racks. With the new storage policy, all pallets of a specific product are located within the same storage zone. This means that the pallets are close to each other, which makes replenishing much easier. Besides, thanks to the improved dock choice and to a lesser extent the storage policy, forklift drivers drive less 'vertical meters' (in front of the docks). As a result, forklift drivers are less likely to run into each other. This decreases driving time and the probability of accidents.

4.7 Conclusions

This chapter introduced two policies to decrease the total driving distance within the warehouse. Together, a theoretical reduction in the total driving distance with 32.5% is achieved.

To improve the storage location of products, the warehouse is split up into 10 zones, see figure 22. Each product is then assigned to one of the ten zones. If there is enough storage space, pallets of this product are stored in this zone. When assigning products to zones, we need to take into account the demand of the product, the storage needs of the product and the average distance from the zone to the inbound and outbound locations. Orders often contain pallets of different products, thus we also want to take correlation in demand between products in demand into account.

To calculate the optimal storage allocation, a BIP model is constructed. Due to the high number of variables, the BIP is unable to calculate the optimal storage allocation. By removing the correlation between products, the BIP is simplified and able to calculate a – close to optimal – solution. A solution for the original problem (with correlation between products) is found by applying a Simulated Annealing algorithm.

Combined with smarter outbound dock choices, the storage assignment policy makes it theoretically possible to decrease the total driving distance within the warehouse with 30%. If this theoretical improvement is realized in practice, the waste of man hours in the warehouse decreases significantly. Ultimately, the decrease in travel distance could lead to fewer warehouse workers which would mean less personnel costs.

However, the theoretical improvement depends on a number of assumptions. One of the main assumptions is that all docks are always free for loading. So each order / ride can be loaded on the optimal dock with the least travel distance from the warehouse. In reality, docks are often occupied and orders have to be loaded at a different loading dock. The main reason for the high dock occupancy is the scheduling policy for releasing rides for picking maintained by the operational planner and desk employee.

In addition to a high dock occupancy, the current policy for releasing rides for picking also results in high peaks in workload (see section 2.5). Improving the scheduling policy could thus help realize the theoretical improvements from the new storage and picking policies, as well as smooth the workload on the warehouse floor. Chapter 5 proposes new scheduling policies which are tested with an simulation model in chapter 6.

5. Alternative scheduling policies

In chapter 4, we formulated two policies that are theoretically able to reduce the total workload in the warehouse with 32.5%. To realize this reduction, we concluded in section 4.7 that the scheduling policy for order picking has to be changed. In addition, an improved scheduling policy can balance the workload throughout the week and day. This chapter proposes a number of scheduling policies.

Section 5.1 explains the use of an order picking scheduling policy and introduces a number of relevant aspects. Key performance indicators to measure the performance of a policy are defined in section 5.2. The different policies are formulated and explained in section 5.3. Thereupon makes section 5.4 a comparison between the policies.

5.1 Aspects of an order picking scheduling policy

A scheduling policy for order picking determines which ride is released for picking at what time and at which dock. It thus has nothing to do with the scheduling of trucks and containers themselves, only with scheduling the processes inside the warehouse. Bolk Logistics has, after all, hardly no influence on the arrival time of external carriers. Therefore Bolk Logistics requires an order picking scheduling policy that can determine in real-time when and where a ride is released for picking.

The main factor for the decision when to release a ride is the booking time of a ride. The booking time is an appointment made by the carrier for loading. The truck or container should thus arrive around the booking time. In addition to the booking time, the expected picking time is relevant as well. If a certain ride takes on average 1 hour to pick, it should be released earlier than a ride with an expected picking time of 30 minutes, given that their booking time is equal. The current work in the pipeline could be considered as well for the decision when and where to release a ride for picking. For example, if order pickers are swamped with work, it makes little sense to release an extra ride.

As soon as a ride is released for picking, order pickers will start picking the required pallets and place them on the set-up outbound area in front of the loading dock. As soon as the truck or containers arrives, the ride can be loaded into the truck or container. Releasing a ride early will likely result in pallets having to wait a long time on the outbound set-up area. If pallets are waiting on the outbound set-up area, the loading dock cannot be used for another ride. The planner then has to wait until the ride is picked up, before a new ride can be released for that specific loading dock. Releasing a ride late will likely result in waiting time for the carrier, as the ride is not ready when the truck or container arrives. In short, when and where to release a ride for picking is a trade-off between flexibility, internal efficiency and carrier contentment. In the next section 5.2, key performance indicators are defined to measure this trade-off.

5.2 Key performance indicators

To evaluate the performance of a policy, performance measures are needed. The warehouse manager currently measures performance of the warehouse by a number of key performance indicators which are evaluated on a weekly basis. To compare scheduling policies, we formulate a number of additional indicators.

The first performance indicator is the average picking time per order. The picking time indicates to what extent the calculated savings from chapter 4 are realized. The scheduling policy has a strong influence on the picking time, as the total driving distance is dependent on the dock choice. We expect a strong correlation between the average number of occupied docks and the picking time. If few docks are occupied, the order is more likely to be loaded at a closer dock and thus have a lower picking time.

The number of occupied docks mentioned above is a good measure for the flexibility of the operation. If few docks are free, options for the planner are limited. As soon as an order is released, the schedule can no longer be changed. As a result, no other rides can be inserted in between. The time an order waits at the set-up outbound area is another indicator of the flexibility of the operation. The longer an order has to wait for the carrier, the longer the dock is occupied. Because of uncertainty in the external carrier arrivals, we expect that the flexibility of the operation is important in coping with deviations.

One of the goals of a new scheduling policy is to balance the workload in the warehouse throughout the day. Most of the external carriers arrive, despite a later booking time, before 15:00, which leads to high peaks in workload in the morning. Especially between 8:00 and 10:00 and between 13:00 and 14:30, the workload is high. By spreading out the workload over the day, warehouse staff will be experience less hustle. In the ideal situation, we could decrease the number of warehouse workers per shift. We can measure the workload by the number of orders loaded per hour of the day and the number of actions (movements of pallets) performed per hour of the day.

Another important aspect of the scheduling policy is the contentment of external carriers. External carriers are contracted by Nouryon and want to be loaded as soon as possible. For them, waiting time is a loss of money. We distinguish two different types of waiting: waiting time before the booking time due to the carrier being early and waiting time after the booking time due to the order not being ready at Bolk Logistics. To measure the different waiting times, we define three indicators: total waiting time, waiting time after booking and the percentage of drivers that has to wait after the booking time.

Lastly, the warehouse supervisor at Bolk Logistics is not interested in an unnecessarily complicated policy for releasing rides for picking. Therefore, we add a fifth dimension called implementability which indicates how easily the policy can be implemented. An important aspect of the implementation is the complexity of the policy. The desk employee should be able to follow the policy without too much hassle. The implementability is determined via expert opinion of the desk employee and the warehouse supervisor.

All performance indicators are summarized in table 3. Together, they give a good impression of the performance of a scheduling policy.

Table 3: Key performance indicators policies for releasing rides for picking

Indicator	Description	Dimension
Picking time	Average picking time per order	Efficiency
Number occupied docks	Average number of docks occupied. A dock is occupied when an order is linked to that loading dock	Flexibility
Waiting time in set-up outbound area	Time an order spends on the set-up outbound area in front of the dock	Flexibility
Number orders loaded	The average number of orders loaded per hour of the day	Workload
Number pallet movements	The average amount of pallet movements per hour of the day	Workload
Total waiting time external carrier	The average time between arrival and departure of external carriers	Satisfaction external carriers
Waiting time after booking external carrier	The average time between booking time and departure of external carriers	Satisfaction external carriers
Percentage waiting after booking	The percentage of external drivers that has to wait after booking time	Satisfaction external carriers
Implementability	A score based on how easily the policy can be implemented	Implementability

5.3 Scheduling policies

This section introduces a number of feasible order picking scheduling policies. The main difference between most of the policies is the decision when and where to release an order for picking. When an order is released for picking, the planner assigns a loading dock to this order and all pallets for this order are picked to the set-up outbound area. The decision when and where to release the extremely important for the outbound logistics. For example, releasing an order as early as possible leads to a lot of work in the pipeline and little flexibility, but short waiting times for external carriers.

We differentiate between four different policy-types:

- Releasing rides based on the number of free docks
- Releasing rides based on booking and/or picking and/or arrival times
- Releasing rides based on the work in pipeline
- Releasing rides based on carrier type (Containers, External carriers, Carrier X)

Please note that policies 2, 3 and 4 only hold for external carriers, as the booking time of Carrier X rides and containers is irrelevant. Additionally, for all policies rides for the next day are released at 8 p.m. to ensure there is enough work in the evening and to ensure rides scheduled at 6 a.m. are ready on time.

5.3.1 Policies based on the number of free docks

The first policy that we should evaluate is the current policy. If we want to compare new storage policies with the current situation, we will first have to evaluate the current situation. The current situation can also be used to validate the simulation model, see section 6.4.

In the current situation, the operational planner does not yet use the optimal dock allocation. This implies that the dock choice is made randomly in the current situation. The new storage allocation is also not yet implemented in the current situation. Therefore, we model the current situation with a random dock choice and with the old storage allocation.

Orders are released as soon as possible in the current situation. In practice, this means that as soon as a ride is finalized, a new ride is released. In general, the planner typically reserves four docks for Carrier X, the external trucking company that loads rides for day n at day $n-1$ by coupling trailers (see section 2.4 "Scheduling outbound logistics"). In addition, two docks are reserved for containers. On the remaining docks, trucks for external carriers are loaded. See figure 28 for a logic flow diagram on the current order releasing policy.

Policy 0 - Current situation
Release rides on a random dock based on booking time as soon as a dock is free

To show the expected savings from the improved strategies found in chapter 4, we formulate policy 1. This policy builds further on policy 0 with the addition of the new storage and picking strategies. For a summary on the new strategies, see section 4.7.

In practice, the new picking strategy provides the operational planner with an optimal dock, i.e. the dock that minimizes the driving distance. In practice, the new storage allocation means that order pickers have to travel less towards locations in the back of the warehouse and more towards locations in the front. In theory, these strategies combined can save up to 32.5 percent of the total driving distance. However, we expect to only realize a fraction of these savings with the current scheduling policy, because the current scheduling policy focusses on keeping al docks occupied. As a result, the optimal dock is often not free.

Orders are released in the same manner as in policy 0, see figure 28.

Policy 1 – Improved dock choice and storing strategy
Release rides on the dock that minimizes driving distance based on booking time as soon as a dock is free

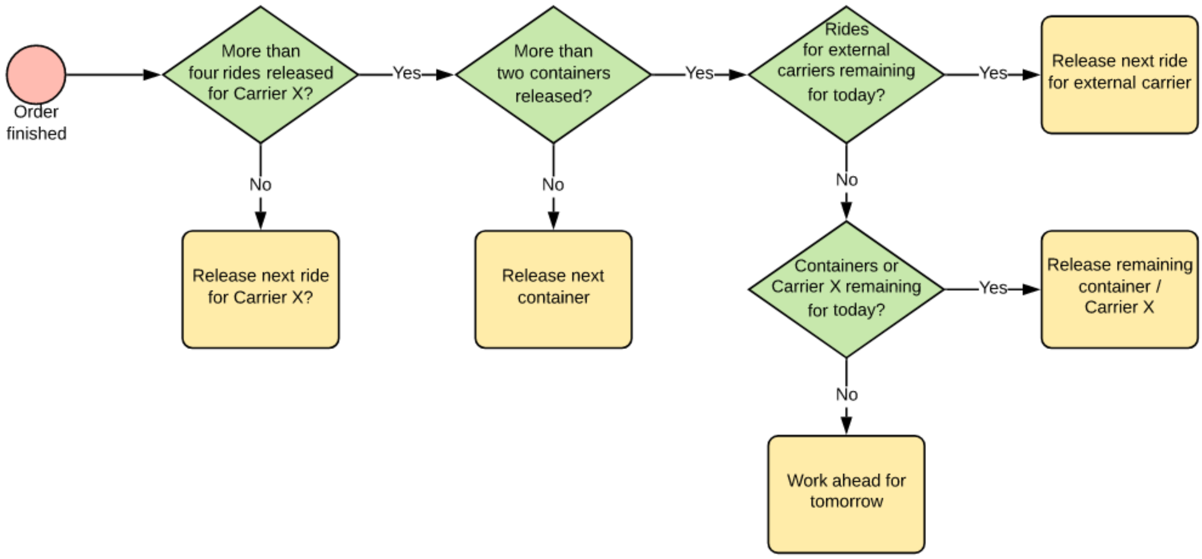

Figure 28: Logic flow diagram policies 0 and 1

5.3.2 Policies based on arrival and/or booking and/or picking times

In the first two policies, as well as in the current situation, docks are occupied as much as possible by the planner. The order for releasing rides for picking is based on the booking time. However, the booking time itself has no influence on the time of release. In this section, we define three policies that postpone the release moment based on the booking time, the arrival time of external carrier or the expected picking time for the ride. All policies in this section implement the new picking and storing strategies as explained in policy 1.

The first policy is based on releasing all rides a fixed amount of time before the booking time. If docks are free at that fixed moment, the ride is released on the dock that minimizes driving distance. If no docks are available, the ride is released as soon as a dock is free. The fixed moment of time before booking time is determined based on preliminary experiments, see section 6.5.3.

Note that this only holds for external carriers, as containers and Carrier X are always present and have no real arrival time. The goal of this policy is to decrease the time a ride has to wait at the set-up compartment for the external carrier. In addition, we expect a decrease in dock occupation and thus an increase in the flexibility of the operation.

Policy 2 – Release rides a fixed time before booking time
Release rides of external carriers on the dock that minimizes driving distance based on booking time on a fixed amount of time before the booking time

In addition to the booking time of the orders, the picking time is relevant as well for the moment of release. By adapting policy 2 by including the expected picking time, the release moment can be determined for each individual order. Policy 2 namely releases all rides the same fixed amount of time before the booking time. By releasing a ride a factor of the expected picking time before the booking time, the moment of release can be determined for each individual ride. The factor of the picking time (i.e. 1.5 times) is used to create a buffer, since work in the pipeline often prevents warehouse pickers to directly start picking. This factor is based on preliminary experiments.

This policy only holds for external carriers, just like policy 2. By including the expected picking time, this policy is able to further decrease dock occupation by individually tailoring the release moment for all rides.

Policy 3 – Release rides a factor of the expected picking time before booking time *Release rides of external carriers on the dock that minimizes driving distance based on booking time minus picking time on a fixed factor of the expected picking time before the booking time*

The final policy within this section includes the arrival time of external carriers. The arrival time often deviates (strongly) from the booking time due to unforeseen circumstances from the external carrier. By releasing rides as soon as a driver arrives, the planner is certain the pallets do not have to wait on the loading dock and thus only occupy the dock for a short time. Releasing based on arrival time, however, sets a precedent of first come, first serve. As an undesirable consequence, the booking time is no longer relevant. Therefore, an additional rule is enacted that ensures a ride is always released on the booking time. Thirdly, a rule is added to distinguish between rides with a high expected picking time and rides with a low expected picking time. The division between high and low expected picking time is made based on a parameter. This parameter is determined based on initial experiments, see section 6.5.3.

Just like policies 2 and 3, this policy only holds for external carriers. While this policy will most likely increase efficiency and flexibility within the warehouse, waiting times for external carriers will rise.

Policy 4 – Release rides at carrier arrival or at booking time *Release rides of external carriers on the dock that minimizes driving distance based on carrier arrival time or booking time (whichever is first) or the expected picking time before booking time (if the expected picking time is higher than a fixed time.*

Figure 29 shows a logic flow diagram describing the policies based on arrival and/or booking and/or arrival time.

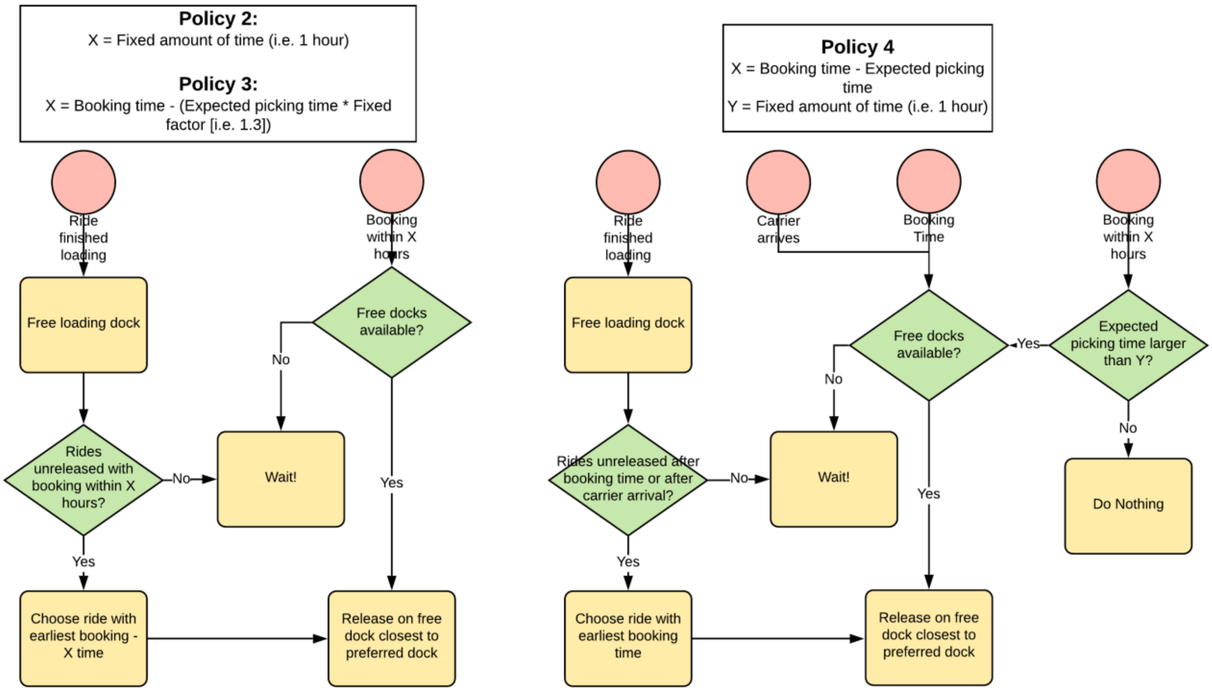

Figure 29: Logic flow diagram policies 2, 3 and 4

5.3.3 Policies based on work in the pipeline

Policies so far are either based on the dock occupation or the booking time of the ride. However, releasing rides when there is still work in the pipeline has little effect. Warehouse pickers only start picking the new ride as soon as all work in the pipeline is finished (or when the planner changes priorities in the WMS). Therefore, we specify a policy to release rides based on the work in the pipeline.

This policy releases a ride as soon as one of the warehouse workers has no work remaining, i.e. when the pipeline is empty. Rides are then released based on booking time. This ensures that all workers will be occupied as much as possible, while still remaining flexible and efficient.

> *Policy 5 – Release rides based on the work in the pipeline*
> *Release rides on the dock that minimizes driving distance as soon as one of the warehouse workers has no work based on the booking time*

Figure 30 shows the logic flow diagram for policy 5.

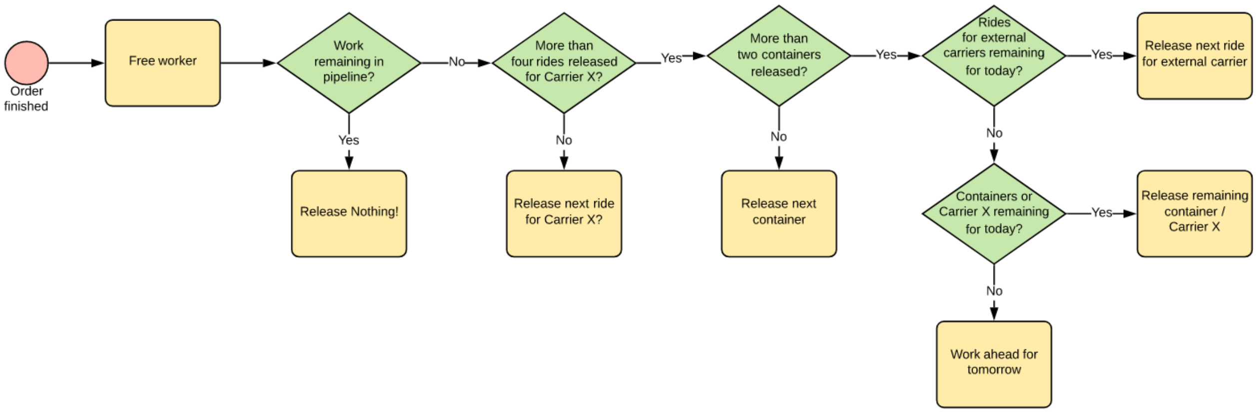

Figure 30: Logic flow diagram policy 5

5.3.4 Policies based on carrier type

All previous policies assume that all rides can be scheduled at every moment. It could however be beneficial to discriminate between different types of rides. For example, while containers can be loaded throughout the entire day, external carriers often arrive before 18:00. In addition, it could create stability if the regular rides are standardized regarding time and location (i.e. fixed loading docks). We formulate two different policies which discriminate between carrier type.

The first policy is based on postponing containers to the end of the day. Currently, rides for Carrier X are loaded at the same time as containers. In this policy, we split these rides by loading rides for Carrier X from 6:00 and containers after all rides for Carrier X are loaded. We do implement a limit for the number of rides for Carrier X of 5 at the same time, because Carrier X is unable to couple and decouple more than 5 trailers at the same time.

If this policy turns out to be effective, it is possible to combine it with one of the policies mentioned before. Initially, we decide to release rides for external carriers a fixed time before the booking time (see policy 2).

Policy 6 – Release containers after all rides for Carrier X are finished
Release rides on the dock that minimizes driving distance based on booking time on a fixed amount of time before the booking time. However, only release containers after all rides for Carrier X *are done*

The last policy is focused on structuring loading docks. In the previous policies, docks are either assigned randomly or based on driving distance. By allocating fixed docks for regular rides (containers and Carrier X), we create stability and regularity. It is most likely not the most efficient policy in terms of driving distance, but it is very convenient for the operational planner. Therefore, it might be an outcome if the differences in KPI's are not too large.

If this policy turns out to be effective, it is possible to combine it with one of the policies mentioned before. Initially, we decide to release rides for external carriers a fixed time before the booking time (see policy 2).

Policy 7 – Release containers and rides for Carrier X on fixed loading docks
Release rides based on booking time on a fixed amount of time before the booking time. Allocate docks to Carrier X and containers and release on the dock that minimizes driving distance within this allocation

Recall that all policies release rides at 8 p.m. for the next day to ensure a steady workflow and to ensure that rides scheduled at 6 a.m. are ready in time. This fact is not taken into account in this section, as it has no influence on the release of rides for today.

5.4 Comparison of alternatives

In the previous section we defined eight different policies that will be evaluated with a simulation model in chapter 6. In this section we discuss the practicality of all policies, i.e. what are the practical implications of the policies for the planner and the warehouse itself.

The first scheduling method (policies 0 and 1) is the current policy and thus the best known. It is easy to implement because it requires hardly no logic: as soon as a dock is free, the planner releases the next ride from the list. The policies based on booking time (policies 2-4) are harder to implement, as the planner has to regularly check which ride to release on which dock. In addition, policy 3 requires additional information about the expected picking time. Policy 5 asks even more from the planner as he has to constantly monitor the work in the pipeline for the order pickers. The challenge with policies 6 and 7 is the concentrated loading of containers. In both policies containers are likely loaded in the late afternoon and evening. This implies that a truck driver from either CTT or Bolk Logistics has to be available to transport containers from and to the container terminal. In other policies, multiple drivers can transport one container and then resume with their normal work.

All policies have their challenges and benefits, but all of them are feasible in practice according to the operational manager. However, he believes additional information is necessary to help his decision making in most of the policies.

5.5 Conclusions

We propose eight alternatives for scheduling the order picking of outbound orders. These alternatives try to mitigate the stochasticity of picking and loading times within the warehouse as well as the stochasticity of external carrier arrivals. All alternative policies make a different decision on when and where to release a certain ride for picking.

The first two policies (0 and 1) represent the current scheduling policy as observed in reality. These policies will mainly be used for verification as well as for benchmarking. Policies 2 till 4 base the decisions when to release a ride for picking on the booking time, the expected picking time and the actual arrival time of the carrier or a combination of these times. Policy 5 is based on the current work in the pipeline. Releasing new orders for picking does not make sense if the pickers still have plenty of work that has to be done before the new order. It would then be better to wait to remain flexible. The last two policies (6 and 7) split the two predictable carriers, Carrier X and CTT (containers).

The scheduling policies are evaluated based on a number of key performance indicators. In essence, the KPI's come down to a trade-off between internal efficiency, flexibility and external carrier contentment. The policies are evaluated by a simulation study in chapter 6.

6. Simulation study

Before implementing one of the eight policies defined in section 5.3 Scheduling Policies, we want to compare the alternatives. Comparing policies could be done in the real system, for example by instructing the operational planner. However, it would take a long time before statistical significant differences occur. By comparing the policies inside a virtual system (i.e. a simulation), we obtain results in a few hours.

Section 6.1 discusses the simulation model itself. The model, a number of assumptions and the implementation of important processes are discussed. Sections 6.2 and 6.3 discuss respectively the input and output data needed for the simulation study. After the model is finished, section 6.4 discusses the verification and validation of the model. Section 6.5 proposes the experimental design of this simulation study. Thereafter results are discussed in section 6.6 and conclusions are drawn in section 6.7.

Our simulation study can schematically be represented by figure 31.

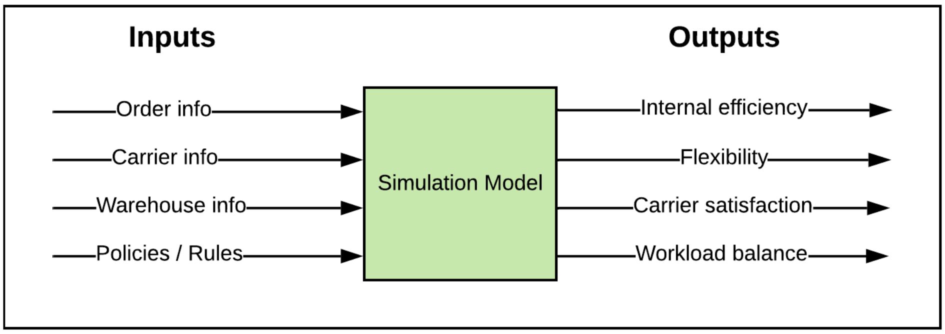

Figure 31: Schematical representation simulation study

6.1 Model description

In this section we introduce the simulation model used to compare the alternative policies. First we discuss the simulation model itself, thereafter we explain our implementation of releasing rides. Lastly, we discuss a number of modelling assumptions.

Recall from section 5.2 Key Performance Indicators that there are five dimensions of the evaluation of proposed methods:

- *Efficiency*: The efficiency within the warehouse affects the time – and number of warehouse workers - needed to perform all pallet movements within the warehouse.
- *Flexibility*: The flexibility of the operation is important because of the stochasticity of variables. The arrival time of external carriers, for example, is uncertain.
- *Balanced workload*: Warehouse workers benefit from a balanced workload throughout the day. Peaks in workload lead to frustrations and a decrease in work morale. In addition, the number of workers needed is dependent on the workload.
- *External carrier satisfaction*: Since Bolk Logistics takes over logistical services of Nouryon, the external carriers are contracted by Nouryon. Therefore, Bolk Logistics has to load the external carriers within the timeframe specified by Nouryon.
- *Implementability*: The desk employee as well as the operational planner needs to be able to easily implement the scheduling policy. Additionally, costs associated with the new policy should be low to convince management to implement the policy.

The goal is to find a policy that balances these five dimensions.

6.1.1 Overview of the model

The model is built with Siemens Plant Simulation; a discrete event simulation tool. This means that the simulation jumps from event to event. It assumes no change in the system occurs between two events. A screenshot of the model with a short description can be found in Appendix H. At the initialization of the simulation, all input variables for the model are set according to section 6.2 and the experiment is initialized. At 18:00 before every working day, all truck rides for the next day are created. Every Thursday, all container orders for the upcoming week are created. Upon creation, actual picking and loading times are determined based on normal distributions. In addition, each truck ride is assigned a booking time through an empirical distribution. Rides for external carriers get an actual arrival time for the truck as well, based on its booking time and an empirical distribution for the deviation from its booking time.

The simulation process starts with releasing rides for picking in accordance with the scheduling policy selected for the experiment. This policy is thus varied across experiments. When a ride is released for picking, it is allocated to a loading dock. As soon as an order picker has finished all previous jobs, he will be assigned to pick the ride. It is thus possible that a released ride has to wait before a warehouse worker will start picking. After picking, the ride is stored on a set-up outbound area. In the model, the set-up outbound area is represented by a buffer with capacity 1. The ride leaves the set-up outbound area towards ready-for-loading when the carrier arrives. For Carrier X and for containers, it is assumed that the carrier is always present. Containers and rides for Carrier X are thus directly moved to loading and skip the buffer area towards ready-for-loading. At the loading station, the ride is again assigned to one of the warehouse workers who will load the truck or containers as soon as all previous work is finished. It is important to note that loading has a higher priority than picking. Additionally, there are workers that only perform picking tasks, workers that only perform loading tasks as well as workers that do both.

See figure 32 for a process flow diagram of the simulation model.

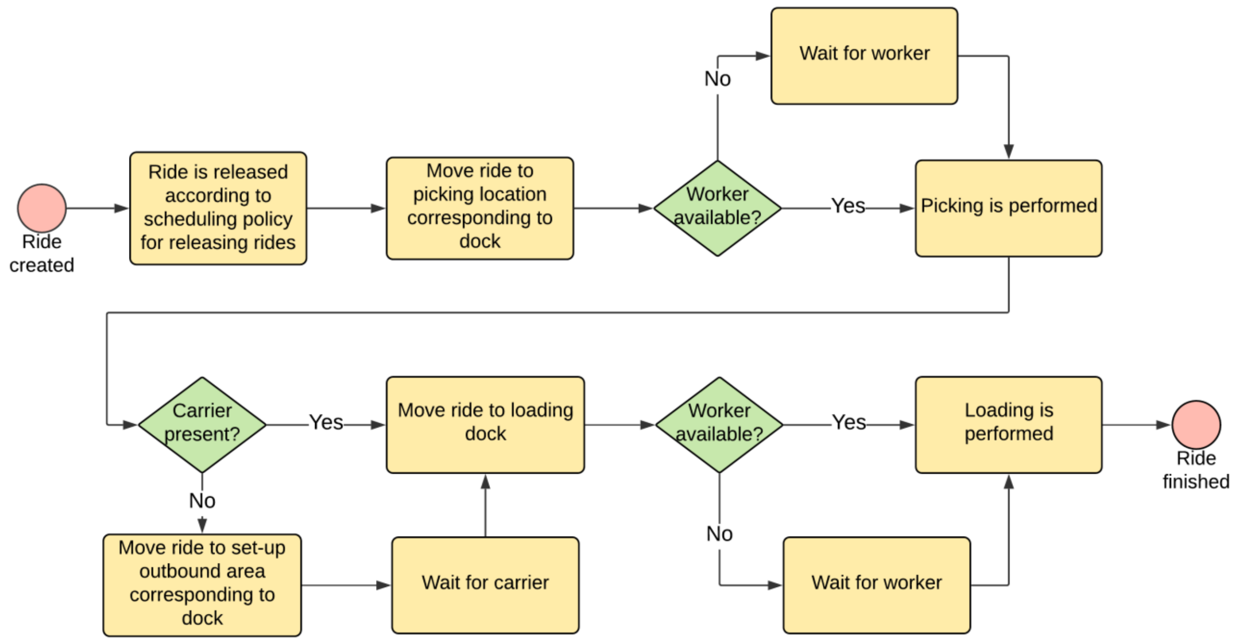

Figure 32: Process flow diagram for simulation model

6.1.2 Modelling of releasing rides for picking

Most of the processes within the warehouse are straightforward and strictly sequential. There are few modeling challenges in these processes. However, the releasing of rides for picking requires a lot of human intelligence. The decision which ride to release for picking and when and where is dependent on a number of variables. Therefore, we modeled each policy independently.

During the day (6:00 until 20:00) someone is available to release rides. The model checks every 5 minutes whether a ride should be released, as well as after a ride is finished loading and a dock becomes available. The model first collects all rides and containers in the system yet to be released and places them in a table. Then this table is sorted based on the active scheduling policy, i.e. booking time or presence of the carrier. Then all rides that violate rules within the scheduling policy such as the maximum number of containers at the same time, are removed from the table. Finally, the ride at the first row of the table is released for picking.

In addition, warehouse staff usually prepares rides for the next day in their last two working hours of the evening shift (20:00 until 22:00). To simulate this in our model, we allow rides for the next day to be released for picking (only) at 20:00. To ensure a number of free docks the next morning, at most 12 docks can be occupied at 20:00.

6.1.3 Implementation of new storage and dock choice strategies

Chapter 4 introduced two strategies for improving the efficiency within the warehouse: a new storage policy and a new dock assignment strategy.

Implementation of the dock assignment policy is straightforward. In the initial situation, the dock is chosen randomly. This is represented in the simulation model by drawing a random number between 1 and 14 and releasing the ride for picking on that dock. If the dock is already occupied, a new random number is drawn. In the new situation, the dock which minimizes the expected picking time is selected. If this dock is occupied, the algorithm will search for the closest dock available.

The implementation of the new storage strategy is modeled by changing the picking frequency of zones. In the current situation, the probability that pallets are picked from a certain bulk storage zone is equal for all bulk storage zones. With the new storage policy, storage zones closer to the docks are likelier to be selected due to storage of fast-movers in the front of the warehouse. The expected savings in picking time in the simulation model for bulk storage are 6.5%. Since picking from the pallet racks does not change, the expected savings in picking time in total are 4.3%.

6.1.4 Modelling assumptions

A simulation model remains a simplification of reality. Therefore, we list our main modelling assumptions and simplifications:

- Only the outbound processes of the warehouses are considered. The inbound and outbound processes are strictly segregated and the inbound processes hardly has any influence on the outbound processes. The inbound process is besides irrelevant for the decision on releasing rides for picking.
- We assume containers and rides for Carrier X can be loaded directly after picking is complete. In practice this implies that the container or truck is ready at the loading dock.
- Rides are loaded and released between 6 a.m. and 8 p.m., while rides can be picked till 10 p.m..
- All truck arrive at the scheduled day, rescheduling of trucks is not incorporated.
- A ride comprises at most two different products. In case a ride consists of two products, each product is responsible for 50% of the pallets.

6.2 Input

The input of the model can be split into two categories: rides and processing times.

6.2.1 Creating orders and rides

Every day of the simulation new truck rides are generated based on historical data. Every Thursday, container orders are generated. An order or ride consists of:

- Carrier (either CTT for containers, Carrier X or External)
- A booking time
- A number of pallets from a specific storage zone

The number of rides per day is based on historical data and has an average of 48, while the average number of container orders per week equals 54. On average 30% of all truck rides is done by Carrier X, hence the remaining 70% is done by external carriers. Recall from section 2.4 (Scheduling outbound logistics) that the booking time of a ride for Carrier X is irrelevant, since their rides are scheduled throughout the day in coordination with their employees. Booking times for containers are always the same, the next Friday at 3 p.m.. This is often the last moment a container can be loaded on a ship boarding for Rotterdam.

The number of pallets in a ride is based on an empirical distribution compounded from historical data where a distinction is made between container loads and truck rides. In addition to the number of pallets, the location of these pallets - which will be linked to the picking time below – is drawn from an empirical distribution.

6.2.2 Processing times

Processing times can be subdivided in picking and loading times. The total travel distance and thus the picking time is dependent on the number of pallets in a ride, the location of these pallets and the outbound loading dock. For the location of the pallets, we use an empirical distribution where half of the pallets come from one storage zone and half of the pallets come from one storage zone (which can be the same as the first storage zone). Then an expected picking time is calculated for each of the fourteen docks. When a scheduling policy for releasing rides uses the closest dock to release, this means in the model that the dock with the lowest expected picking time is chosen. Lastly, the real picking time for each dock is calculated with:

$$\frac{Numberr\ of\ Pallets}{2} * (Exp.picking\ time\ from\ storage\ zone\ 1\ to\ dock * RandomNr1 \\ + Exp.picking\ time\ from\ storage\ zone\ 2\ to\ dock * RandomNr2)$$

The random numbers are based on a normal distribution which is based on historical picking data. The random numbers are the same for all docks, such that the ratio between the expected picking time and the real picking time is the same for all docks.

On the other hand, the loading time for a ride only depends on the number of pallets. Distances to be traveled are namely the same for all docks. Therefore the loading time per ride can be determined by the following formula:

$$Number\ of Pallets * Avg\ loading\ time\ per\ pallet + \sqrt{number\ of\ pallets} * StDev\ loading\ time\ per\ pallet$$

According to historical data, we can use a normal distribution for this formula with μ = 55 seconds and σ = 32 seconds.

The last moment in time that is relevant is the actual arrival time of an external carrier. Recall from section 2.4 (Scheduling outbound logistics) that external carriers often arrive earlier or later than their booking time. By calculating the deviation from the booking time for all external rides in the previous month (July 2019), we are able to create a histogram of the deviation from booking time, see figure 33. This histogram is then tested for a normal distribution. For an alpha of 0.95, we accept this normal distribution with μ = -0.5 and σ = 2.2. In reality, the actual arrival time is also dependent on the booking time. Rides scheduled at

6 a.m. often arrive later, while rides scheduled at 8 p.m. often arrive earlier. Due to insufficient data points, we were compelled to ignore this relation. It is therefore important to check the validity of external arrivals in the verification and validation of the model.

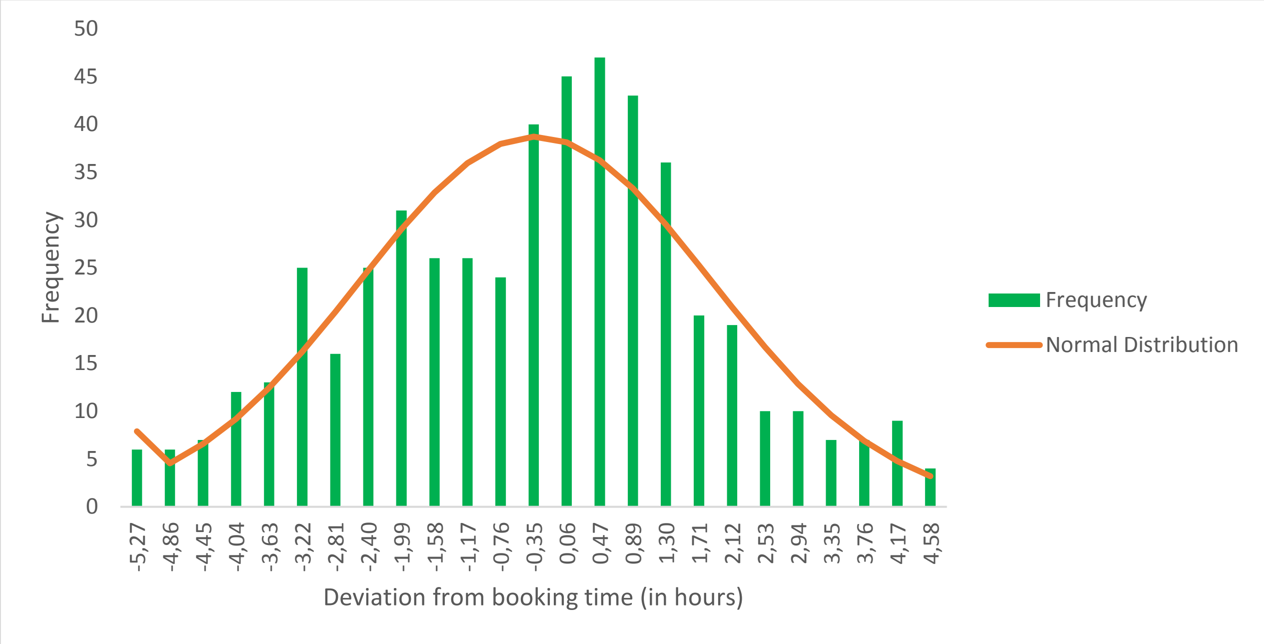

Figure 33: Deviation in arrival time from booking time (below zero is later than booking time)

6.3 Output

The output of the simulation model is linked to the key performance indicators introduced in section 5.2 (Key performance indicators). The interpretation of the performance indicators in the simulation model is as follows:

- Average picking time per order: time a worker in the model spends picking the order.
- Average number of occupied docks: the average number of docks that contain an order, either waiting, picking or loading, between 6:00 and 16:00.
- Waiting time on dock: the time between time finished picking a ride and the start of loading.
- Orders loaded per hour: the variance of the average number of orders loaded per hour. For all loading hours (6:00 till 20:00), the average number of orders loaded is computed. Thereafter, the variance between these averages is computed to show the deviation in workload during the day.
- Actions performed per hour: the variance of the average number of orders loaded per hour. Here the same calculations as for the orders loaded per order is used, except it takes into account individual pallet movements.
- Total waiting time external carriers: the time between arrival of the external carrier and the moment that a warehouse worker starts loading the ride, regardless of booking time.
- Waiting time after booking time: the time between on the one hand the maximum of the arrival time and the booking time and on the other hand the time that a warehouse worker starts loading.
- Percentage waiting: the percentage of external carriers that has to wait for over fifteen minutes after their booking time before a warehouse worker starts loading.

6.4 Validation and Verification

After building the model, it is paramount to confirm the accuracy of the simulation model. This conformation can be achieved through validation and verification. The model has been verified and validated according to the process described by Robinson (1997), see figure 34. The flow of orders throughout the model is checked visually by running the model at slow speed. In addition, the code has been checked by debugging every time after writing a few lines.

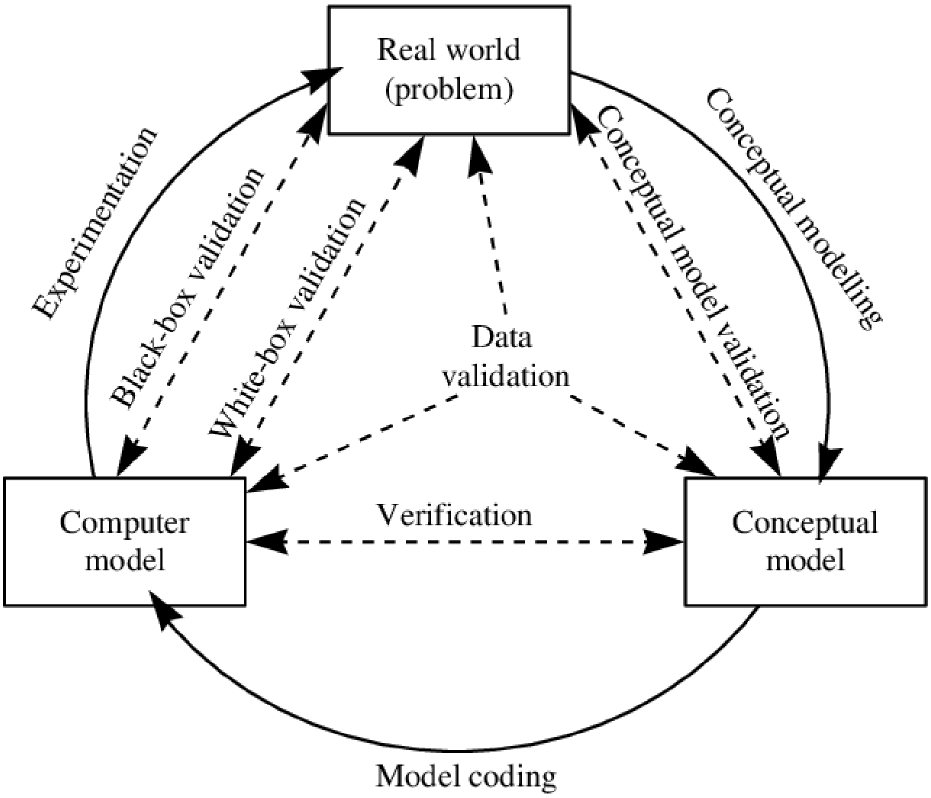

Figure 34: Validation and verification of the simulation model (Robinson, 1997)

Validation of the model is done by comparing the output of the simulation model with the real output. Robinson (1997) describes this process as black-box validation, as the simulation model is seen as a black box (figure 35). Since the input values are derived from the real system, we expect the results of the model to match with the real results. Since the results from the simulation model and the real world are independent from each other (one is in a simulation model and one is in the real world), we cannot use a paired t-test to compare the results. Therefore we have to use the chi-square goodness of fit test. We compared the results from the simulation study with real world on the following indicators:

- The moment in time an external carrier arrives at the warehouse
- The time an order has to wait after picking before loading starts
- The moment an order is finished picking compared to its booking time
- The moment in time an order is finished loading

All three indicators are not directly dependent on the input variables and are thus suitable to test the validity of the simulation model. More details about these tests can be found in Appendix C.

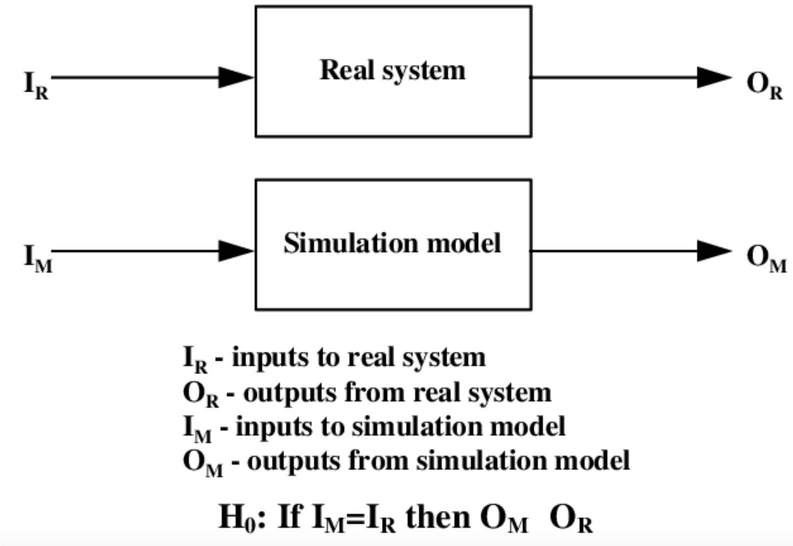

Figure 35: Black box validation (Robinson, 1997)

Lastly, face validation was performed by the operational planner and the warehouse process specialists at Bolk Logistics. They confirmed that the process in the simulation model, as well as its in- and output distributions match with the observed system results.

6.5 Experimental design

Recall from chapter 5 that we want to evaluate eight different scheduling policies for releasing rides with the simulation model. Before conducting experiments, an experimental design is constructed. First a warm-up period is calculated. Thereafter the run length and the number of replications are determined. Lastly, scenarios for evaluating scheduling policies are defined.

6.5.1 Warm-up period

The simulation consists of a non-terminating system, as containers have a booking time at the end of the week and can thus be loaded on quieter days. This creates correlation between days within a week. In addition, the bustle of day n determines how late the warehouse staff can start preparing rides for day $n + 1$. As a result, a busy day is often followed by another busy day. This holds for Fridays as well, since rides for Monday are already prepared Friday afternoon.

To be able to compare policies, we are interested in steady-state performance. Therefore we introduce a warm-up period to determine when the system arrives in a steady-state. To compute the warm-up period, we use Welch's graphical method (Law and Kelton, 1991). We base the warm-up on the multiple KPI's for the initial situation. We compute the warm-up periods in days. See Appendix D for the calculations on the warm-up period. We found that a warm-up period of 14 days or 2 weeks is sufficient for the model to arrive in a steady-state. As a rule of thumb, we set the run length to ten times the warm-up period (140 days) to ensure we collect sufficient data.

6.5.2 Number of replications

Each experiment is ran multiple times to ensure statistical significant results. To calculate the number of replications needed, we use a replication-deletion approach (Law and Kelton, 1991). Each replication has its own initialization and warm-up period. The main benefit of the replication-deletion approach over other methods is the elimination of correlation between replications.

We calculate the number of replications via the sequential procedure (Law and Kelton, 1991), such that a confidence level of 95% is obtained. We solve the following equation for n by sequentially adding replications:

$$\frac{t_{\frac{\alpha}{2},n-1} * \frac{\sigma}{\sqrt{n}}}{\mu} \leq 0.05$$

The number of replications is calculated for all KPIs. The relevant calculations can be found in Appendix E. The highest number of replications needed to ensure statistical significant results with a confidence level of 95% is 37 for the KPI "Waiting time for external carrier after booking time".

6.5.3 Parameters for scheduling policies

Most of the scheduling policies for releasing rides defined in section 5.3 "Scheduling policies" are dependent on one or multiple parameters. To be able to compare the different policies in the next section, we need to determine the parameters per policy. All policies depend on the number of rides for Carrier X and the number of containers that are permitted to occupy a dock at the same time. Recall from section 2.4 ("Scheduling outbound logistics") that the reason for this restriction is that is unrealistic to expect too many trailers from Carrier X or too many containers to be present at the same time. The maximum number of rides for Carrier X at the same time is set to 3 and the maximum number of containers is set to 2. For policies 6 and 7, rides for Carrier X and containers are pooled together. In practice, this will mean that Bolk Logistics has to allocate one of their truck drivers to couple and de-couple containers full time. In the simulation model, we set the sum of rides for Carrier X and containers to 5 for policies 6 and 7.

Most policies have individual parameters as well. These are explained below. Note that all parameter settings are determined by expert opinion and initial simulation experiments. For a quick overview, see table 4 in section 6.5.4 below.

Policies 0, 1 and 5 are independent of any parameters.

Policy 2, releasing rides for picking based on their booking time, releases rides a fixed amount of time before the booking time. If this fixed moment is too close to the booking time, this policy shows similar results as policy 4. If the fixed moment is too far removed from the booking time, it shows similar results to policy 1. Therefore it is paramount to choose the parameter such that the policy delivers distinctive results. Therefore we set the fixed moment to release a ride for picking to 50 minutes before the booking time.

Similarly to policy 2, policy 3 has a parameter that determines when a ride is released is picking. For policy 3, this parameter is the factor of the expected picking time. If this factor is chosen too low, similar results as policy 4 will be obtained. If the factor is too high, similar results to policy 1 are obtained. To ensure distinctive results, we set the factor of the expected picking time to 1.3. Rides will thus be released 1.3 times their expected picking time before the booking time.

Policy 4 releases rides for external carrier either when the carrier arrives, the booking time is due or the expected picking time before the booking time. The parameter for this policy is the boundary for when rides are released the expected picking time before booking time. If this boundary is chosen too high, no rides are released earlier based on picking time, which leads to high waiting times for external carriers. When choosing the boundary too low, all rides are released based on picking time and no rides are released based on booking time or arrival time.

Policy 6 only releases containers after all rides for Carrier X are finished. Policy 6 has the same parameter as policy 2, as rides for external carriers are released a fixed amount of time before the booking time. To facilitate meaningful comparisons, we set this fixed amount of time to 50 minutes, Lastly, policy 7 only releases containers on specific docks. There is thus no parameter for these rides. On the other hand, external rides are released based on their booking time, just as policy 2. To facilitate meaningful comparisons, we set this fixed amount of time to 50 minutes,

6.5.4 Policies

We want to evaluate the follow policies with interventions with the simulation model:

0) *Current situation*: Release rides on a random dock based on booking time as soon as a dock is free
1) *Improved dock choice and storing strategy*: Release rides on the dock that minimizes driving distance based on booking time as soon as a dock is free
2) *Release rides a fixed time before booking time:* Release rides of external carriers on the dock that minimizes driving distance based on booking time at 50 minutes before their booking time
3) *Release rides a factor of the expected picking time before booking time:* Release rides of external carriers on the dock that minimizes driving distance based on booking time minus picking time at 1.3 times their expected picking time before the booking time.
4) *Release rides at carrier arrival or at booking time or the expected picking time before booking time:* Release rides of external carriers on the dock that minimizes driving distance based on carrier arrival time or booking time (whichever is first) or based on expected picking time if the picking time is larger than a fixed time.
5) *Release rides based on work in the pipeline:* Release rides on the dock that minimizes driving distance as soon as one of the warehouse workers has no work based on the booking time
6) *Release containers after all rides for* Carrier X *are finished:* Release rides on the dock that minimizes driving distance based on booking time at 50 minutes
7) *Release containers and rides for* Carrier X *on fixed loading docks: Release rides based on booking time 50 minutes before the booking time. Allocate docks 15, 18, 21, 24 and 28 to* Carrier X *and containers and release on the dock that minimizes driving distance within this allocation.*

All policies are explained in detail in section 5.3 ("Scheduling policies') and summarized in table 4 below.

Table 4: Parameters per scheduling policy

Policies	Random / Closest dock	Smart storage Yes / No	Short explanation	Specific parameters
0	Random	No	Current situation	-
1	Closest	Yes	Current situation with new storing and picking strategies	-
2	Closest	Yes	Fixed time before booking	50 minutes before booking
3	Closest	Yes	Fixed factor of expected picking time before booking	1.3 times expected picking time before booking
4	Closest	Yes	At carrier arrival or booking time or expected picking time before booking time (if exp. picking time > fixed number)	Expected picking time of more than 50 minutes is released before booking time
5	Closest	Yes	Based on work in pipeline	-
6	Closest	Yes	Containers after Carrier X	External rides 50 minutes before booking
7	Closest	Yes	Containers and Carrier X on specific docks	External rides 50 minute before booking and containers and Carrier X on docks 15, 18, 21, 24 and 28

6.6 Results

All of the eight policies are ran for 37 replications with a warm-up period of 14 days and a run length of 140 days. Specific parameters for each scenario can be found in table 4 above.

Recall from section 5.2 ("Key performance indicators") that key performance indicators to measure the performance of scheduling policies for releasing rides for picking are divided into five dimensions:

- Internal efficiency
- Flexibility of the operation
- Balance of workload over the day
- External carrier satisfaction
- Implementability

The first four KPI dimensions are outputs from the simulation model. The final dimension, implementability, relates to the cost of implementation and is based on expert opinion from the warehouse supervisor. The cost of implementation consists of training costs, eventual extra personnel and changes needed in the process.

Results from the simulation model are split up between dimension. Figures 36 till 39 provide the most important key performance indicators per dimension from the simulation study. Detailed results can be found in table 5. Full results with confidence intervals can be found in Appendix F. Please note that for each of the performance indicators holds that the lowest value is the best.

Table 5: Numerical results simulation study

Policy	Average Picking Time (s)	Dock Occupation	Average Time On Dock (s)	Variance of Pallets Per Hour	Waiting Time After Booking (s)
0	2005	13,24	19968	3011	2156
1	1919	13,19	20353	3404	1922
2	1834	8,99	15097	1794	2640
3	1828	8,55	14917	1695	2638
4	1821	8,17	14681	1659	1583
5	1828	9,70	17878	3501	1103
6	1833	7,97	13786	1553	2329
7	1901	9,52	14770	2100	6220

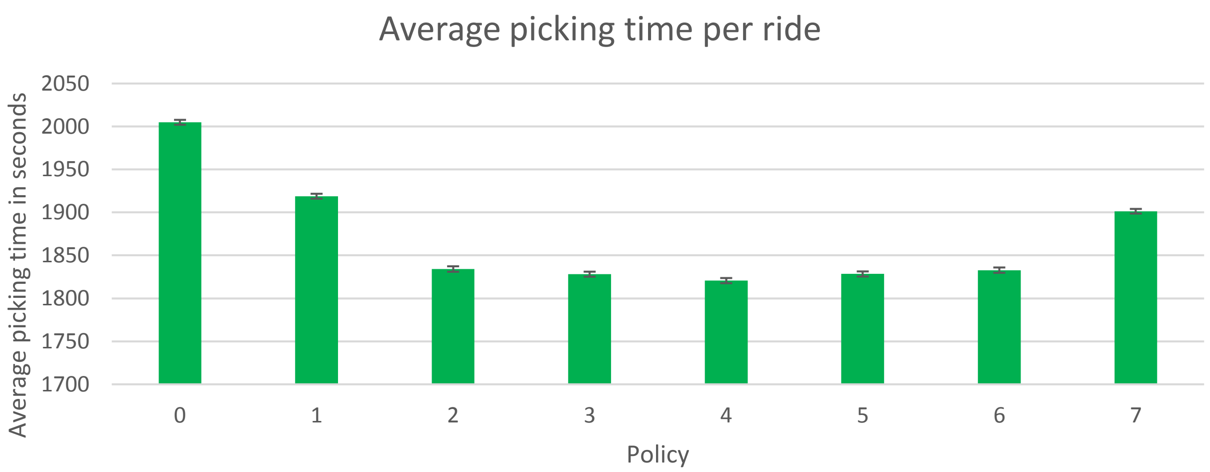

Figure 36: Internal efficiency - average picking time per order

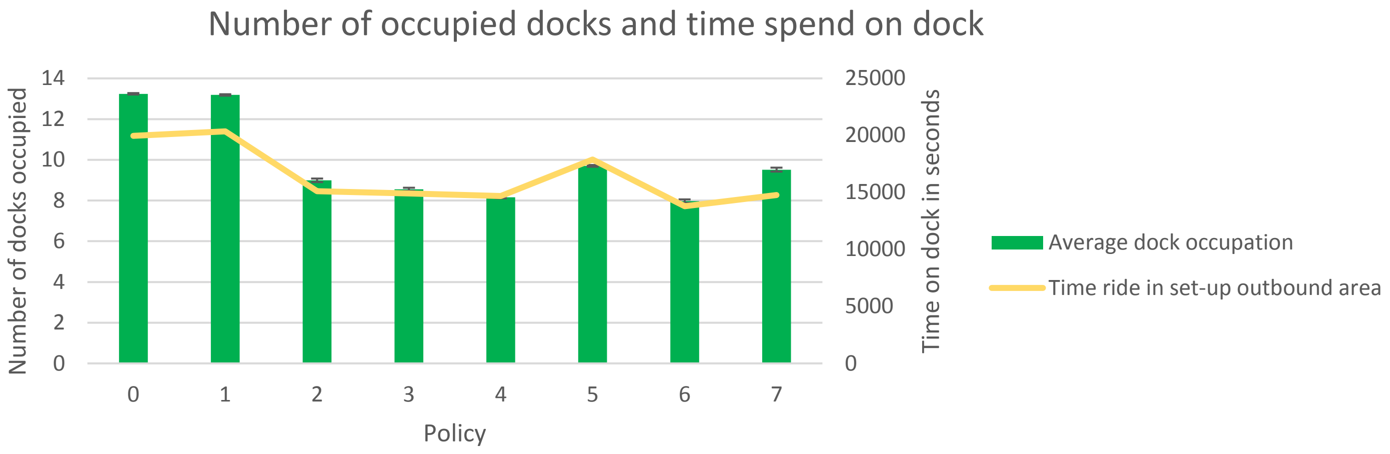

Figure 37: Flexibility - dock occupation and time waiting at set-up outbound area

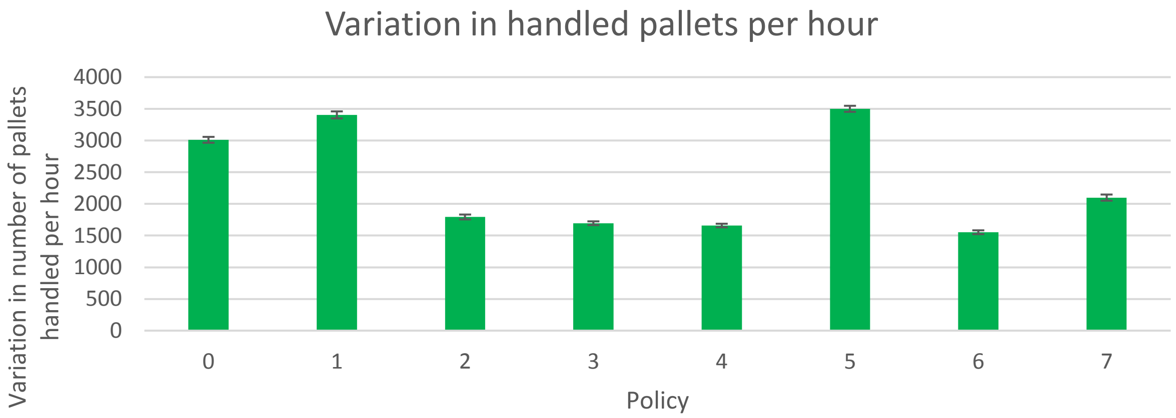

Figure 38: Balance in workload - variation in pallet movements per hour

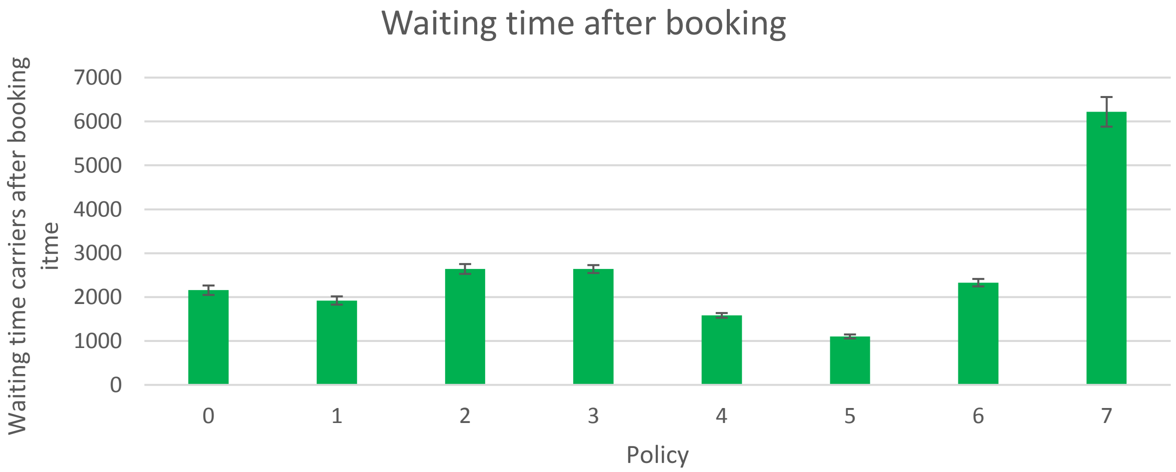

Figure 39: Carrier satisfaction: average waiting time for external carrier after their booking time

As explained above, the implementability factor is a score assigned by expert opinion based on the cost of implementation. The higher this score, the costlier the implementation of the policy.

0) Policy 0 is the current policy and therefore has no extra costs for implementation.
1) The only additions for policy 1 are the new dock and storage strategies. The dock allocation requires a bit more attention from the desk employee when releasing rides for picking, since he has to allocate the ride to the correct dock.
2) Policy 2 requires the desk employee to keep an eye on the booking time, in addition to the optimal dock. This requires a change of mindset, since there no longer is a trigger (i.e. previous ride is finished) for releasing a ride.
3) Policy 3 requires an additional calculation based on the booking time.
4) In contrast with policies 2 and 3, policy 4 does have a simple trigger. Either the booking time is passed or the external carrier arrives.
5) Policy 5 requires the desk employee to keep an eye on the different type of workloads in the warehouse. In addition, warehouse staff needs to be guided more.
6) Policy 6 is the easiest for the desk employee, aside from the current policy. The costs for this policy lie in the availability of an extra driver in the evening to transport the containers.
7) Policy 7 only requires the desk employee to remember the specific loading docks for Carrier X and containers. Otherwise the policy is equal to policy 2.

The assigned scores for the implementability are displayed in figure 40.

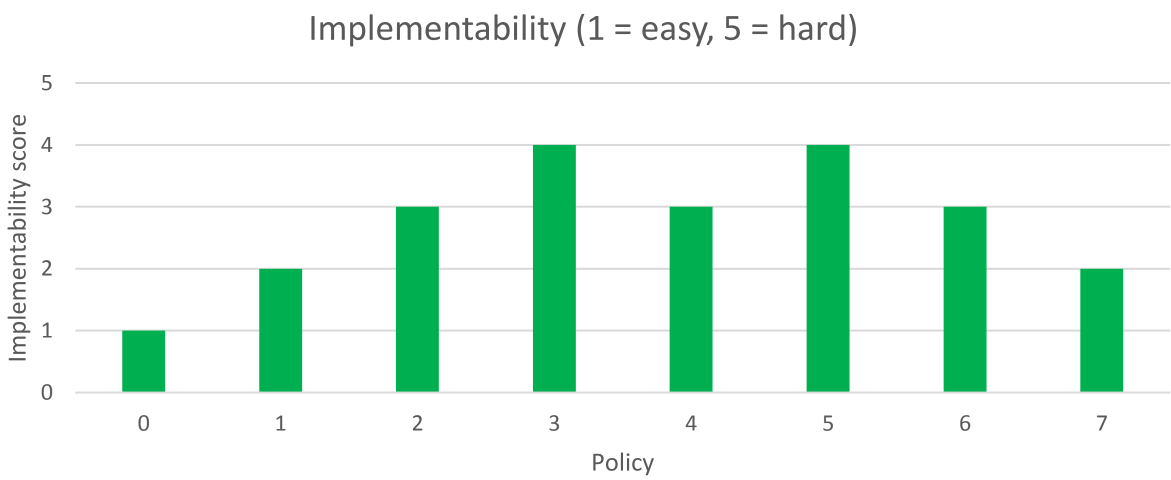

Figure 40: Implementability score

When analyzing the figures above, we conclude there is not one policy which dominates all other policies, which means there is no clear best policy. Policy 7, however, does not score in the top three of a dimension once. Assigning specific loading docks to Carrier X and containers does apparently not work. Therefore we disregard policy 7 in further analysis.

In section 6.2 ("Input") we state an expected decrease in picking time between the current situation (policy 0) and the new storage strategy (policy 1) of 4.3%. If we look at the internal efficiency chart (figure 36), we conclude that the improvement in picking time per ride equals exactly 4.3%. This means that the new storage allocation works exactly as intended.

By looking at differences between policy 0 and 1, we conclude that the new storage and dock assignment strategies should definitely be implemented. It however still remains difficult to compare the remaining policies based on figures 36 till 40. To be able to compare the alternative scheduling policies for releasing rides for picking, we perform a multi-criteria analysis. We calculate a score between 1 and 5 for each policy

(1 is lowest, 5 is highest), except policy 7, for each dimension. This score is based on the relative positioning of the policy with the other policies. When multiple KPI's per dimension are used, a score is given for each of the KPI's. Thereafter, the scores are averaged such that we have one score per dimension. An overview of all scores per policy is shown in the radar charts in figure 41.

According to management, all dimensions are equally important. Therefore, we give every dimension a weight of 1. Final scores are displayed in table 6. We see that overall policy 4 performs best. Recall that policy 4 releases rides when an external carrier arrives, at the booking time or earlier when the expected picking time of that ride is longer than 50 minutes.

Table 6: Normalized results simulation study

Policy	Efficiency	Flexibility	Workload	Carrier Satisfaction	Implementability	Final score
0	1,00	1,12	2,01	2,62	5,00	**2,35**
1	2,87	1,02	1,10	3,15	4,00	**2,43**
2	4,71	4,21	4,36	1,21	3,00	**3,50**
3	4,84	4,43	4,85	1,00	2,00	**3,43**
4	5,00	4,65	4,60	3,50	3,00	**4,15**
5	4,83	3,10	1,72	5,00	2,00	**3,33**
6	4,74	5,00	4,53	1,83	3,00	**3,82**

Figure 41: Radar charts of the results of the simulation experiments

6.7 Conclusions

By means of a simulation study, we evaluated 8 different scheduling policies for releasing rides for picking. A scheduling policy determines which ride at what moment is released for picking. The simulation model generates new rides based on historical data. The simulation model is verified and validated. The scheduling policy has a high influence on the outbound operations in the warehouse. Its effects are subdivided into five dimensions: efficiency, flexibility, external carrier satisfaction, balance of workload and implementability.

A number of conclusions can be drawn from the comparison between policies:

1) The new dock allocation and storage strategies should be implemented by Bolk Logistics. Both provide more efficiency in the warehouse, while increasing external carrier satisfaction. The costs of implementing is low compared to the improvement in efficiency.
2) Scheduling policies that release rides based on a time related to the booking (policies 2, 3 and 4), strongly increase efficiency and flexibility within the warehouse. The operational costs to run the warehouse will thus decrease. However, rides will more often be too late on the set-up outbound area, which means that external carriers are more likely to wait.
3) Scheduling policies that release rides based on work in the pipeline will release rides relatively early. Besides, workers in the morning shift are much busier than workers in the evening shift which leads to an unbalance in workload over the day. On the other hand, this policy ensures rides are timely loaded.
4) Scheduling containers after all rides for Carrier X are done is a viable option, but leads to high costs, because there has to be a truck driver available every evening to couple and de-couple containers. In other policies, this is not needed as the truck planner plans multiple drivers who each will couple and de-couple one or two containers during their regular day shift.
5) Assigning fixed docks to Carrier X and/or containers does not work. It limits options within the warehouse, thereby decreasing efficiency and flexibility.

When comparing all alternatives with a multi criteria decision analysis, we conclude that policy 4 performs best. This policy releases rides for picking when:

- The external carrier arrives
- The booking time of the ride is reached
- The booking time minus the expected picking time is reached, if the expected picking time is over 50 minutes.

7. Conclusions and recommendations

Now that all results are known, we are able to answer the main research question. Section 7.1 draws conclusions from our research and discusses the limitations and contributions to scientific literature. Section 7.2 explains the recommendations for Bolk Logistics in practice. Lastly, recommendations are made for further research in section 7.3.

7.1 Conclusions

The following research goal was formulated in section 1.4 for this research:

To find adaptions in the process design at Bolk Logistics Hengelo that streamline the material handling within the warehouse.

From the problem statement (section 1.3) and the current situation analysis (chapter 2), we conclude that there are multiple possible adaptions for the process design at Bolk Logistics. While describing the material flow throughout the warehouse, the current situation analysis reveals a number of inefficiencies:

1. Long travel distances for putting away and order picking of pallets due to
    a. Random dock allocation for outgoing rides
    b. Randomized storage within bulk storage
2. High peaks in workload in material flow
3. Little flexibility in the warehouse operation due to working (far) ahead

In the literature review, we classified the warehouse of Bolk Logistics as a contracted warehouse with little influence on the incoming and outgoing material flow. Only the internal material flow can easily be adapted. Literature distinguishes between random, dedicated and class based storage. Bolk Logistics uses a class based storage with only two classes namely pallet racks and bulk storage. There is not one single storage policy found in literature which fits all the needs of the warehouse for Bolk Logistics.

To improve the storage policy, we increase the number of storage classes in the bulk storage zone from one to ten. Each product is allocated to a zone and batches are stored randomly in one of the storage locations within this zone. Products are allocated to a zone based on average needed storage space, average throughput and interaction with other products. A BIP is formulated which is able to solve the allocation problem optimally. However, the problem size is too large. Therefore, a simulated algorithm is used to determine the near optimal allocation of products.

The dock assignment problem is solved by advising the loading dock that minimizes driving distance for the ride to the desk employee. By selecting the correct loading dock for an outbound ride, the driving distance can be significantly decreased. This advice is given with a business intelligence that provides nearly real-time data. This business intelligence tool is also used to support other operational decisions.

Together, a tactical improvement – product allocation to storage zones – and an operational improvement – visualizing the optimal loading dock - achieve a theoretic reduction in travel distance of 32.5%. These two improvements thus decrease problem 1: 'long travel distances for putting away and order picking of pallets'.

The theoretical improvements are however not realized in reality, mainly because of a lack of flexibility. We conclude that the only influenceable factor herein is the moment when an outbound ride is released for picking. As soon as the ride is released, the loading dock is deemed occupied. Therefore, we define eight different scheduling policies for releasing rides for picking.

These policies are evaluated by a means of a simulation study. We found that the best policy for releasing rides for picking is:
"Release rides for external carriers when the carrier arrives at the warehouse or at the booking time (for orders with an expected picking time under 50 minutes) or at the expected picking time before the booking time (for orders with an expected picking time over 50 minutes)."
In practice, this means that rides with a lot of pallets from the pallet racks, and thus with a high expected picking time, are earlier released for picking. Rides with a lower expected picking time are released when either the driver arrives for pick-up or when the driver is scheduled to arrive. This policy is efficient in practice because of the uncertainty in the arrival of external carriers. As explained in section 2.4 ("Scheduling outbound logistics"), carriers are often too early or too late.

To return to the research goal, we found three adaptions in the process design that streamline the internal material flow:

1. Real-time advice on dock assignment
2. New class based storage policy
3. New scheduling policy for releasing rides for picking

7.1.1 Scientific contributions

The contribution to literature is limited as most of the research is strongly focused on the use case at Bolk Logistics. The situation at Bolk Logistics is fairly specific as they are a third party logistics provider with a single customer and located next to the production site. Especially the policies for releasing rides for picking are tailored to the needs of Bolk Logistics, it is unlikely that the policies are useful for another logistics provider.

On the other hand, our storage policy does contribute something new to literature. We were able to combine the OOS and the COI into a storage allocation policy which is able to:

- Deal with capacities in different storage zones
- Model correlation between products that are often sold together
- Select the close to optimal outbound point for each combination of products

There is currently no known method in literature which is able to select the optimal outbound dock while taking the correlation between products into account.

The simulated annealing algorithm used in this research is not groundbreaking. However, it shows another method how to penalize the algorithm in the objective function with a linear component.

7.1.2 Limitations

Our research has some limitations. The main limitation is the little availability of data. The operation for Nouryon started in September 2018, but was only taken over in full in July 2019. During this period, warehouse staff was learning how to work with the products and the warehouse management system. Data obtained from the operation in this time period is no longer relevant, as the warehouse staff now work significantly faster. Due to this limitation, relevant data is only obtained for a few months.

Recall from section 4.4.1 that the simulated annealing algorithm makes a number of assumptions. It assumes that a maximum number of two products are in one order, storage zones are never full and loading docks are always free. As a result of these assumptions, projected savings in travel distance are most likely overestimated.

The main limitation for the simulation study is its scope, only the outbound process is considered. However, the material flow in the inbound process influences the outbound process. For example, when the material inflow is high, an employee from the outbound process will help with the material inflow.

7.2 Recommendations for practice

To benefit from the results of this research Bolk Logistics should implement the new storage and dock allocation policies and change their scheduling policy. None of these changes require high investment costs.

First of all, we advise Bolk Logistics to increase the number of storage zones in the bulk storage from one zone to ten zones. This is easily implementable in the WMS without high investment costs.

- We advise to implement the storage zones incrementally. No research is done towards the number of storage zones. The choice for ten zones simply follows from the number of aisles times two. It might be wise to first start with a few zones to introduce the working method to the warehouse staff and to evaluate the results.
- The simulated annealing algorithm assumes that storage zones are never full. It is advised to keep an eye on the number of free locations per storage zone and adapt the product allocation accordingly. A BI-tool is created as part of this research to indicate how much space is left in each storage zone, see Appendix G.2.
- The average stock per product and the average throughput time per product are dynamic. It is thus paramount to keep updating the product allocation iteratively. We advise to revise the allocation every other month. A BI-tool is created to support decisions on product level, see Appendix G.3..

Secondly, we advise Bolk Logistics to implement our tool (see Appendix G.1) to show in (nearly) real-time which dock is most suitable for each outbound ride. It is a powerful supporting tool for the desk employee. It does however require a daily manual update. In the future, this update could be automated or the advice could be provided by the WMS. The latter is however costly.

Lastly, we advise to change the policy for releasing rides for picking. This requires no investment. We do the following recommendations:

- The new scheduling policy has an influence on the client, Nouryon, as their external carriers will no longer be loaded directly when they arrive. This especially occurs when the carrier arrives too early. This consequence should be coordinated with Nouryon.
- Since workload will be divided more evenly over the day, it is even more important to manage the warehouse staff. Instead of doing secondary tasks, such as making space and counting product, in the evening, these tasks should be spread evenly over the day.
- We advise to run a pilot with the desk employee for a number of days to evaluate the results of the new policy in practice. It is then important to test the policy on busy as well as quiet days to ensure the policy performs as designed in both cases. If the policy indeed improves efficiency and flexibility without a sharp increase in waiting times, we advise to definitive implement the policy.

7.3 Recommendations for further research

As mentioned in the recommendations for practice, we advise Bolk Logistics to further investigate the optimal number of storage zones. This can be done in two ways, in practice or in theory. By testing it in practice, the number of zones can manually be adjusted in the WMS. However, each time the number of zones is adjusted, the operation has to be idle for two hours. This is rather difficult as the operation is normally live 24 hours per day, 7 days per week. Testing in theory can be done by adapting the simplified BIP model from section 4.3 or the simulated annealing algorithm from section 4.4.

Secondly, it is interesting for Bolk Logistics to further expand the simulation study. Dependencies between material inflow processes and material outflow processes, for example, could be taken into account. Another important aspect is combining inflow and outflow processes. Currently, each forklift is selected for either putting away or picking products.

Lastly, as mentioned in the problem cluster in section 1.3, a lot of administrative tasks are complex or redundant and are automatable. Under those administrative tasks falls the creating and releasing of rides for picking. As we provided a strict policy with this research, it is possible to let a software system make the decisions. This will however be costly to implement.

8. Bibliography

Bartholdi, J. J., & Hackman, S. T. (2008). *Warehouse & Distribution Science: Release 0.89* (p. 13). Supply Chain and Logistics Institute.

Richards, G. (2017). *Warehouse management: a complete guide to improving efficiency and minimizing costs in the modern warehouse*. Kogan Page Publishers.

Gu, J., Goetschalckx, M., & McGinnis, L. F. (2007). Research on warehouse operation: A comprehensive review. *European journal of operational research*, *177*(1), 1-21.

Van den Berg, J. P., & Zijm, W. H. (1999). Models for warehouse management: Classification and examples. *International journal of production economics*, *59*(1-3), 519-528.

Min, H. (2006). The applications of warehouse management systems: an exploratory study. *International Journal of Logistics: Research and Applications*, *9*(2), 111-126.

Rouwenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G. J., Mantel, R. J., & Zijm, W. H. (2000). Warehouse design and control: Framework and literature review. *European journal of operational research*, *122*(3), 515-533.

Petersen, C. G. (1999). The impact of routing and storage policies on warehouse efficiency. *International Journal of Operations & Production Management*, *19*(10), 1053-1064.

Kallina, C., & Lynn, J. (1976). Application of the cube-per-order index rule for stock location in a distribution warehouse. *Interfaces*, *7*(1), 37-46.

Mantel, R. J., Schuur, P. C., & Heragu, S. S. (2007). Order oriented slotting: a new assignment strategy for warehouses. *European Journal of Industrial Engineering*, *1*(3), 301-316.

Heskett, J. L. (1963). Cube-per-order index-a key to warehouse stock location. *Transportation and distribution Management*, *3*(1), 27-31.

Hausman, W. H., Schwarz, L. B., & Graves, S. C. (1976). Optimal storage assignment in automatic warehousing systems. *Management science*, *22*(6), 629-638.

Petersen, C. G., Aase, G. R., & Heiser, D. R. (2004). Improving order-picking performance through the implementation of class-based storage. *International Journal of Physical Distribution & Logistics Management*, *34*(7), 534-544.

Van den Berg, J. P. (1996). Class-based storage allocation in a single-command warehouse with space requirement constraints. *International Journal of Industrial Engineering*, *3*, 21-28.

Book, R. V. (1980). Michael R. Garey and David S. Johnson, Computers and intractability: A guide to the theory of $ NP $-completeness. *Bulletin (New Series) of the American Mathematical Society*, *3*(2), 898-904.

Xavier-de-Souza, S., Suykens, J. A., Vandewalle, J., & Bollé, D. (2009). Coupled simulated annealing. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, *40*(2), 320-335.

Law, A. M. and Kelton, W. D. (1991) Simulation modeling and analysis, McGrawHill New York doi: 10.1145/1667072.1667074.

Banks, J., Carson, J. S., Nelson, B. L., & Nicol, D. M. (1996). *Discrete-event system simulation* (Vol. 3). Upper Saddle River, NJ: Prentice hall.

Robinson, S. (2004). *Simulation*. John Wiley & Sons, Ltd.

Heerkens, H., & van Winden, A. (2017). *Solving managerial problems systematically*. Noordhoff.

Introduction to LP_Solve. (2019). Retrieved from http://lpsolve.sourceforge.net/5.5/

Robinson, S. (1997, December). Simulation model verification and validation: increasing the users' confidence. In *Winter Simulation Conference* (pp. 53-59).

A. Simplified BIP model

The BIP model of section 4.2 is simplified as mentioned in section 4.3. By removing correlation between products, the assignment problem can be solved optimally by the Cube per Order Index (COI). Below the BIP model for this assignment problem.

Indices of sets

i	Products that need to be stored in bulk storage (1-100)
z	Zones where products can be stored (1-10)

Parameters

$LocProd_{i,z}$	Number of locations needed to store product i in zone z
$CapLoc_z$	Number of locations in storage zone z
$Totaldist_z$	Total travel distance per pallet stored in zone z. Consists of distance traveled to store and to load.
$Demand_i$	Number of pallets loaded of product i

Decisions

$X_{i,z}$	1 if product i is stored in zone z, 0 otherwise

Objective function

Minimize:

$$\sum_i \sum_z X_{i,z} * Totaldist_z * Demand_i$$

Constraints

$$\sum_z X_{i,z} = 1 \ \ \forall\, i \qquad (1)$$

$$\sum_i (X_{i,z} * LocProd_{i,z}) \ \le CapLoc_z \ \ \forall\, z \qquad (2)$$

$$X_{i,z}\ \{0,1\} \ \ \forall\, i, z \qquad (3)$$

Constraint (1) ensures that each products is stored at a location. Constraint (2) makes sure capacity is not exceeded. Lastly, constraint (3) sets the decision variable to binary.

Results can be found in figure 42.

Results:

[Redacted]

Figure 42: Results simplified linear programming model: Storage allocation per product

B. Results SA algorithm

[Redacted]

Figure 43: Results simulated annealing algorithm: Storage allocation per product

C. Validation of simulation model

Section 6.4 discusses the validation of the simulation model. We compare results from the simulation model with expected results from reality.

The arrival of external carriers is not incorporated in the input data, as we only used the average deviation from the booking time. It is thus not evident from the input data whether the arrival times of external carriers corresponds with their actual arrival times. With the chi-squared test, we found a p-value of 0.035 which implies that we are unable to conclude that there is no statistical difference. However, we do continue with this distribution, as it is better that carriers arrive earlier than in reality than later.

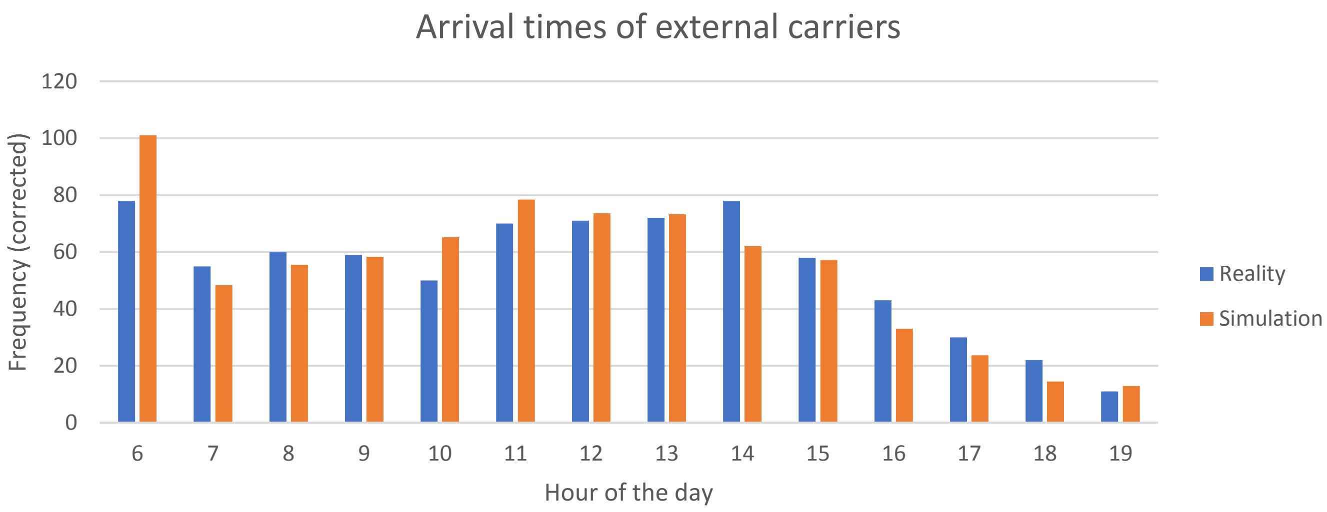

Figure 44: Validation of arrival times external carriers

Secondly, we analyzed the waiting time of an order at the set-up outbound area. Here, we found a p-value of 0.052 which implies that there is no statistical difference.

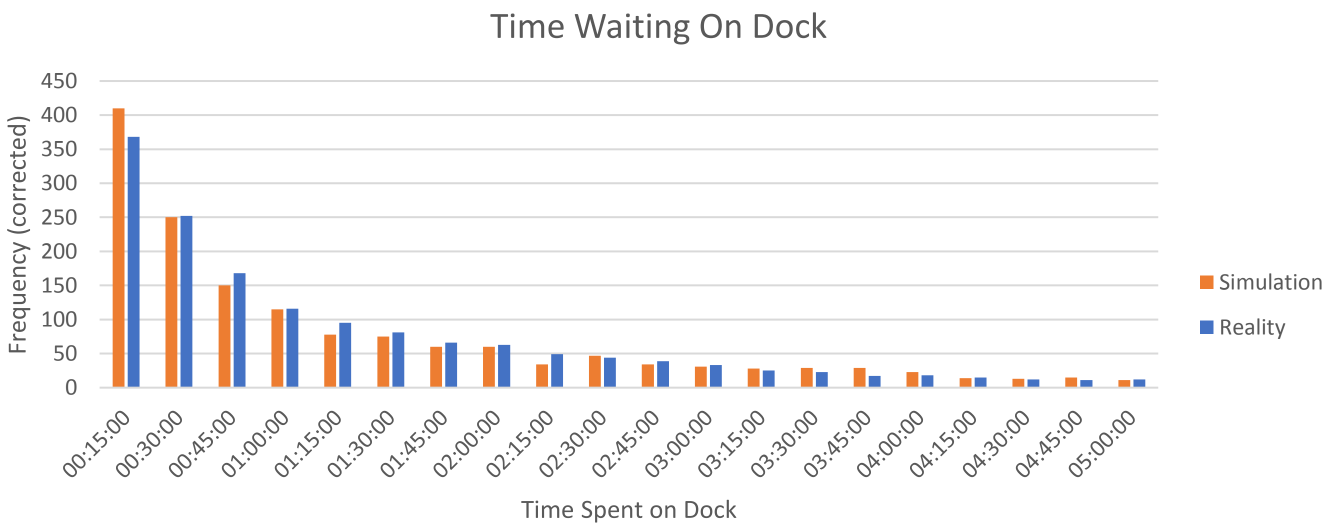

Figure 45: Validation time spent at set-up compartment

Thirdly, we analyzed the moment in time an order arrives at the set-up outbound area and compared that moment with the booking time of the order. Here we found a p-value of 0.075.

Table 7: Validation moment finished picking

Moment finished picking	Sim	Perc Sim	Real	Perc Real	Error
Before Booking	1363	72,5%	1319	70,1%	1,4678
After Booking	314	16,7%	337	17,9%	1,5697
During Booking	204	10,8%	226	12,0%	2,1416

Lastly, we validated the moment an order departs from the warehouse. This analysis shows the distribution of workload throughout the day. Here we found a p-value of 0.051.

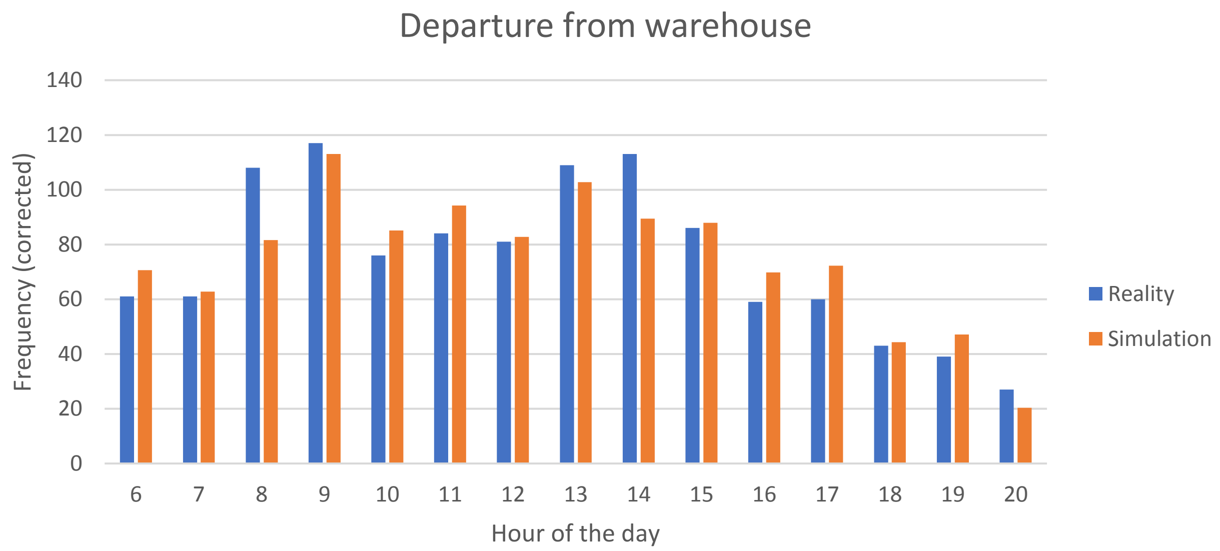

Figure 46: Validation departure rides from simulation model

D. Warm-up period

We base the warm-up period on Welch's graphical method, see section 6.5.1 for an explanation. All calculations are done based on 5 independent simulation runs of 150 working days.

First, we look at the total number of outbound rides in the simulation model per working day, so excluding Saturday and Sunday. The number of total outbound rides should be stable to ensure a steady state of the model. Differences within a week can be explained by division of containers over the week. We see that a relative steady state is entered around t=11.

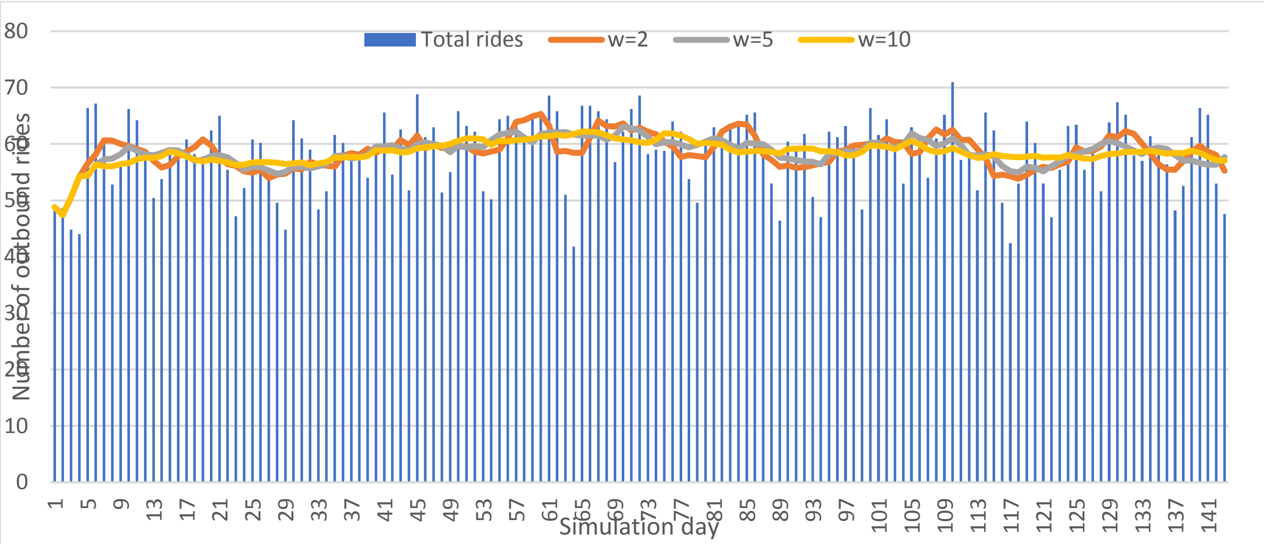

Figure 47: Warm-up period number of outbound rides

Secondly, we look at the waiting time on dock. This is the time between the end of picking and the start of loading. We notice a steady state performance from t=9.

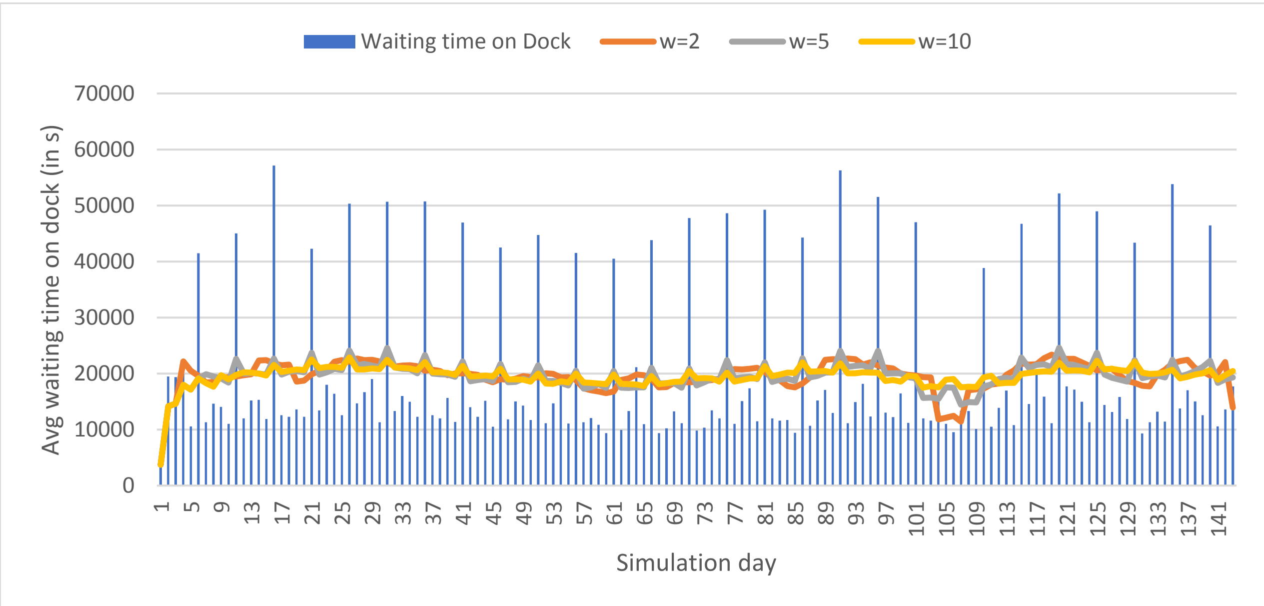

Figure 48: Warm-up period average waiting time at set-up outbound area

Lastly, we analyze the total waiting time after the booking time. This is the time external carriers have to wait after their booking time. The high peaks can be explained by rides which were delayed till after a weekend. Here, we also see a steady state from t=9.

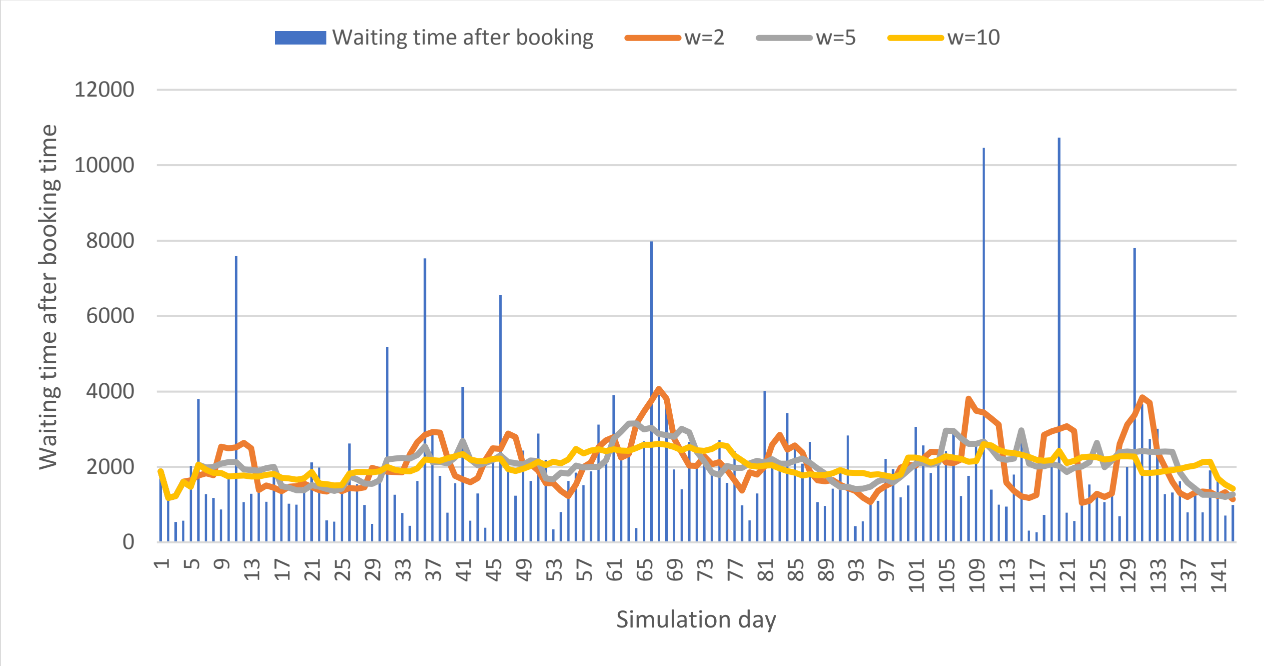

Figure 49: Warm-up period waiting time after booking time

In conclusion, we see that the maximum number of working days required for the system to come into a steady state equals 11 days. This corresponds with 14 days in the simulation model itself.

E. Number of replications simulation study

Recall from section 6.5.2 that we calculate the number of replications needed for multiple KPI's. In this appendix we discuss the findings from these calculations.

First, we calculate the value of half the confidence interval width divided by the mean with:

$$\frac{t_{\frac{\alpha}{2},n-1} * \frac{\sigma}{\sqrt{n}}}{\mu}$$

Here, n is the number of replications so far. By increasing n, we – generally speaking – decrease σ as well. We increase n until we meet the acceptable threshold of 0.05.

We start with the KPI 'waiting time for external carriers". Here, the number of replications needed equals 19.

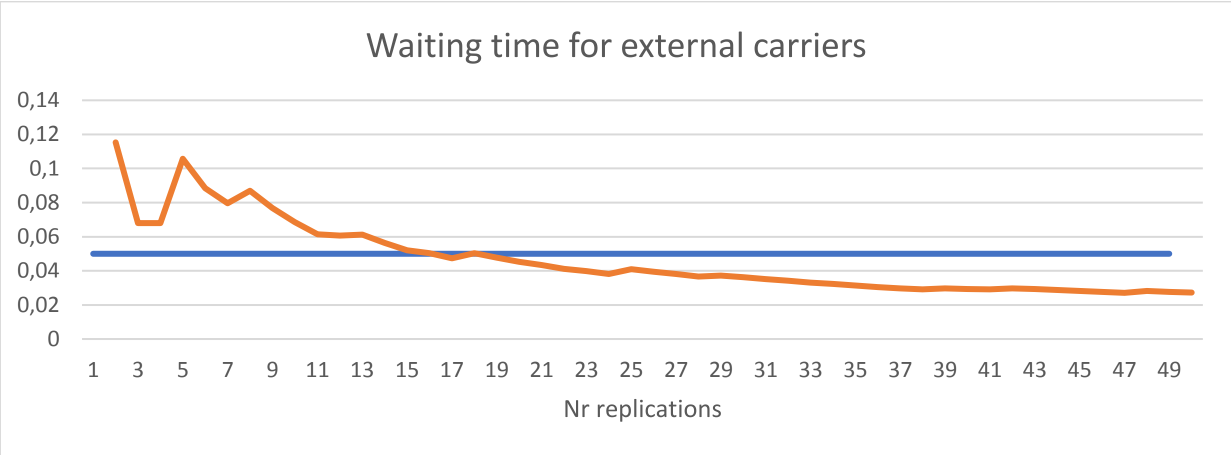

Figure 50: Number of replications waiting time external carriers

Then we calculate the number of replications for the variation in number of pallets handled per hour of the day, i.e. the division of workload over the day. We find that 9 replications are necessary.

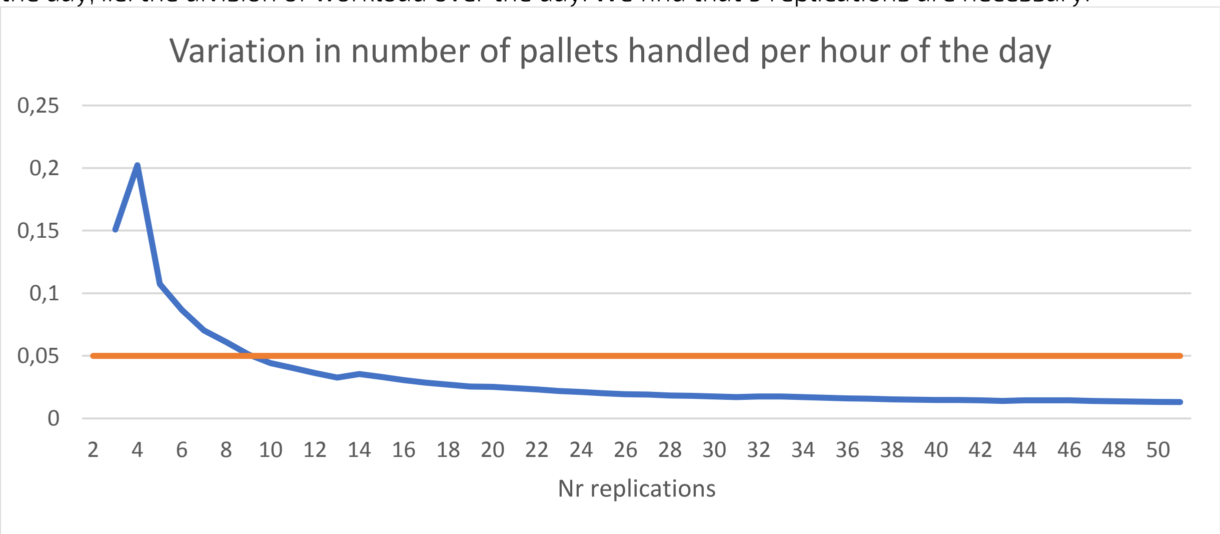

Figure 51: Number of replications variation in number of pallets handled per hour

Lastly, we calculate the number of replications for the waiting time of external carriers after booking time, which equals 37.

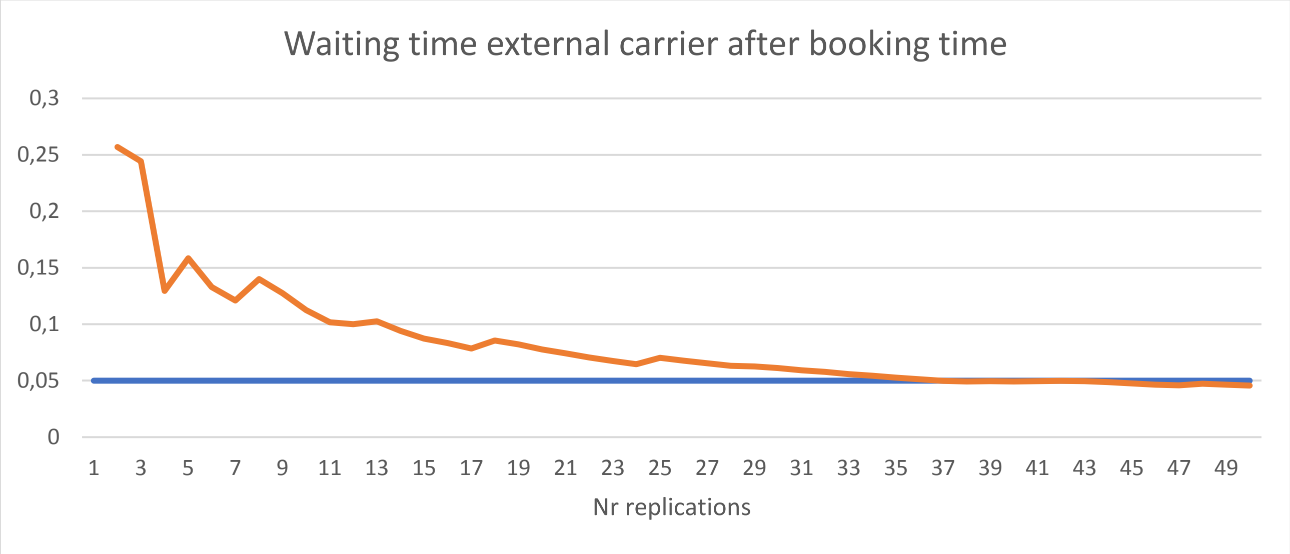

Figure 52: Number of replications waiting time after booking

In conclusion, we set the number of replications for all experiments to 37.

F. Simulation results

Here the results of the final experiment can be found. Each scenario represents one scheduling policy.

Averages per experiment of all KPI's

Exp	1 AvgPickTime (s)	2a DockOccupation	2b AvgTimeOnDock (s)
1	2005	13,24	19968
2	1919	13,19	20353
3	1834	8,99	15097
4	1828	8,55	14917
5	1821	8,17	14681
6	1828	9,70	17878
7	1833	7,97	13786
8	1901	9,52	14770

Exp	3a AvgOrdersPerHo	3a VarOrdersPerHour	3b AvgPalletsPerHour	3b VarPalletsPerHour	3c PercWaitingWorkerS	3c PercWaitingWorkerS
1	4,13	1,48	167	3011	9,4%	29,6%
2	4,14	1,62	167	3404	10,2%	33,4%
3	4,10	1,18	167	1794	18,2%	28,3%
4	4,10	1,08	167	1695	19,3%	27,3%
5	4,09	1,16	167	1659	18,8%	28,3%
6	4,13	1,42	167	3501	11,7%	36,7%
7	4,02	1,21	166	1553	25,3%	20,2%
8	4,11	1,36	167	2100	15,9%	27,2%

Exp	4a WaitingTimeCarı	4b WaitingTimeAfter	4c PercWaitingCarrier
1	4672	2156	23,7%
2	4352	1922	21,5%
3	6425	2640	31,2%
4	6488	2638	33,3%
5	3562	1583	22,4%
6	3724	1103	13,8%
7	6134	2329	29,2%
8	10081	6220	41,9%

Confidence intervals per experiment of all KPI's

Exp	1 AvgPickTime (s)	2a DockOccupation	2b AvgTimeOnDock (s)
1	(2002,03 - 2007,71)	(13,21 - 13,28)	(19746,11 - 20189,16)
2	(1916,01 - 1921,72)	(13,15 - 13,22)	(20149,73 - 20556,52)
3	(1830,94 - 1837,3)	(8,9 - 9,08)	(14952,3 - 15242,15)
4	(1825,19 - 1831,06)	(8,47 - 8,63)	(14773,87 - 15060,26)
5	(1817,68 - 1823,65)	(8,11 - 8,22)	(14540,05 - 14822,49)
6	(1825,41 - 1831,33)	(9,66 - 9,74)	(17692,01 - 18064,84)
7	(1829,72 - 1835,94)	(7,88 - 8,06)	(13599,89 - 13971,82)
8	(1898,69 - 1904,07)	(9,42 - 9,62)	(14624,74 - 14915,83)

Exp	3a AvgOrdersPerHour	3a VarOrdersPerHour	3b AvgPalletsPerHour	3b VarPalletsPerHour	3c PercWaitingWorkerShift1	3c PercWaitingWorkerShift2
1	(4,11 - 4,15)	(1,45 - 1,51)	(166,11 - 168,14)	(2965,04 - 3057,57)	(-0,26 - 0,45)	(-0,46 - 1,05)
2	(4,11 - 4,16)	(1,59 - 1,65)	(166,12 - 168,15)	(3349,05 - 3459,73)	(-0,27 - 0,48)	(-0,39 - 1,06)
3	(4,08 - 4,13)	(1,16 - 1,21)	(166,13 - 168,16)	(1755,48 - 1832,03)	(-0,36 - 0,72)	(-0,23 - 0,8)
4	(4,08 - 4,12)	(1,05 - 1,1)	(166,12 - 168,14)	(1665,32 - 1724,56)	(-0,35 - 0,73)	(-0,24 - 0,79)
5	(4,07 - 4,12)	(1,12 - 1,19)	(166,08 - 168,11)	(1630,63 - 1687,25)	(-0,24 - 0,61)	(-0,36 - 0,92)
6	(4,1 - 4,15)	(1,39 - 1,46)	(166,13 - 168,16)	(3452,95 - 3548,18)	(-0,24 - 0,47)	(-0,29 - 1,02)
7	(4 - 4,05)	(1,17 - 1,25)	(165,45 - 167,48)	(1522,35 - 1583,02)	(-0,45 - 0,95)	(-0,12 - 0,53)
8	(4,08 - 4,13)	(1,33 - 1,39)	(166,16 - 168,19)	(2051,41 - 2147,94)	(-0,41 - 0,73)	(-0,25 - 0,79)

Exp	4a WaitingTimeCarrier (s)	4b WaitingTimeAfterBooking (s)	4c PercWaitingCarrier
1	(4533,75 - 4810,38)	(2048,94 - 2263,77)	(0,23 - 0,24)
2	(4222,72 - 4480,29)	(1827,45 - 2016,63)	(0,21 - 0,22)
3	(6303,97 - 6545,24)	(2528,41 - 2752,08)	(0,3 - 0,32)
4	(6385 - 6591,23)	(2548,12 - 2728,68)	(0,32 - 0,34)
5	(3500,27 - 3624,23)	(1529,4 - 1636,72)	(0,22 - 0,23)
6	(3651,66 - 3795,93)	(1057,25 - 1148,77)	(0,13 - 0,14)
7	(6040,2 - 6228,76)	(2244,39 - 2413,31)	(0,29 - 0,3)
8	(9744,48 - 10418,19)	(5881,82 - 6557,74)	(0,41 - 0,43)

G. BI-tools

This appendix describes all business intelligence tools which are created in support of this research.

G.1 Order planning assistance tool

The order planning assistance tool predicts for each ride scheduled for today where each pallet is stored. It distinguishes between pallets stored in the 'Bulk', 'Pallet Racks' and at the producer ('Akzo'). The prediction of the tool is not 100% correct, as the scheduling sequence might change throughout the day. The tool requires a manual import each morning of all rides scheduled for today.

In addition to the location of the pallets, the tool also calculates the optimal dock allocation, e.g. the dock which minimizes driving distance for order picking.

[Redacted]

Figure 53: BI tool order planning

G.2 Stock overview per storage zone

This tool shows the number of free storage location within each bulk storage zone. Additionally, the number of pallets stored at the moment and the utilization of the locations within this zone. The tool is automatically daily updated based on the WMS.

Warehouse workers use this tool to see where space is needed within the warehouse.

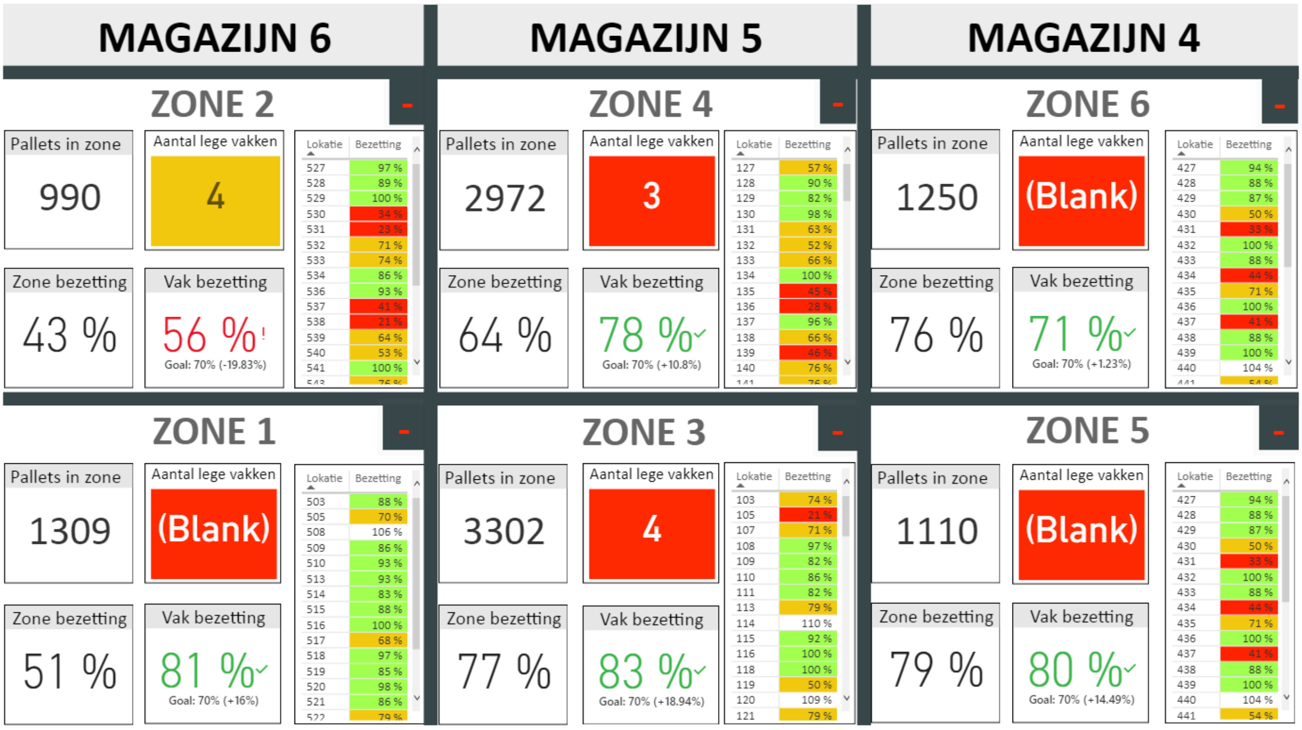

Figure 54: BI tool inventory overview per zone

G.3 Allocation per product to storage zones tool

This tool is used check iteratively for each product where it should be stored. This could be in the pallet rack system, or in one of the six bulk storage zones. This decision is made based on:

- Average batch size

- Average inventory
- Average throughput time
- Average demand

All of these indicators are based on data of the last 60 days, such that changes in product behavior is noticed early.

Artikel: All

Locatie Klasse: All

Alle data is gebaseerd op de afgelopen 60 dagen!

Artikel	Omschrijving	Locatie Klasse	Rest Locatie klasse	SH	Grenswaarde	Aantal Batches	Gem. Batchgrootte	Stdev Batchgrootte	Gem Voorraad	Gem Verblijftijd	Hoev Uitslag
4311	SUPRASEL F PE 25KG*40 GPEF 1000	5FAST	5REST	3	28	11	195	12.31	940	19.73	3059
4438	BROXO 6-15 PROFESSIONAL PE 25KG*40	5FAST	5REST	3	28	14	204	53.28	802	11.84	3465
8019934	BROXO 6-15 PROF PE 25KG*49 NHIF	4EXP	5REST	3	22	12	196	2.93	759	13.25	2588
4397	SUPRA 0.6 N2 F PE 25KG*40 GPEF 1000	5FAST	5REST	3	28	7	204	80.68	583	20.29	1722
8019967	KNZ LICK UNIVERSAL 10KG*140 NHLF 1400.	6SLOW	5REST	4	30	7	85	35.80	354	38.76	824
8019003	KNZ LICK BASIC 100 25KG*45 EHEF 112	5SLOW	5REST	4	38	1	100	0.00	324	100.01	714
4408	SUPRA 0.9 N2 F PE 25KG*40 GPEF 1000	5FAST	5REST	3	28	8	135	48.04	324	12.56	1212
4447	SALINA SALT 6-1525KG*40 EHEF	5FAST	5REST	3	28	5	117	3.87	310	20.03	925
4396	SUPRA 0.5 N2 F PE 25KG*40 GPEF 1000	5FAST	5REST	3	28	7	155	33.75	300	14.64	1311
4313	SUPRASEL F PE 25KG*40 EHEF 1000	6FAST	5REST	3	28	5	109	20.33	289	19.57	748
4407	SUPRASEL UNS PE 25KG*40 GPEF 1000	5FAST	5REST	3	28	8	111	11.92	286	13.62	1066
8019931	SUPRASEL F PE 25KG*49 NHIF 1225.	4EXP	5REST	4	30	5	99	0.80	279	21.99	873
3784	KNZ LICK STANDARD 10KG*112 EHEF 112	4EXP	5REST	4	38	9	72	18.16	251	17.72	820
4409	SUPRASEL UNS PE 25KG*40 EHEF 1000	5SLOW	5REST	3	28	2	75	0.00	250	76.95	448
4394	SUPRA 0.9 N2+20 I3 F PE 25KG*40 GPE	5FAST	5REST	3	28	7	156	27.43	246	11.38	1207
4383	AN FEED SALT UNS PE 25KG*40 EHEF 10	6FAST	5REST	3	28	6	128	28.87	243	13.27	1061
8019919	NEZO ARA F PP 1KG*12 WR*105 NHIF 1260.	4EXP	5REST	4	30	7	116	38.04	222	8.33	818
4437	BROXO ZOUT TABLETTEN PE 25KG*40 EHE	5FAST	5REST	3	28	12	224	16.37	218	3.79	3027
3675	JOZO 23 I NL PP 1KG*12 WR*105 LWIF	5SLOW	5REST	4	30	3	99	1.41	196	33.43	528
8018159	SUPRASEL ONEGRAIN TS-M100, BIGBAG 8	BB	BB	1	1				179	149.67	197
8019918	NEZO ARA F PP 1KG*12 WR*120 NHIF.	4EXP	5REST	3	22	8	93	27.58	178	9.61	790
4403	SUPRASEL M PE 25KG*40 GPEF 1000	6FAST	5REST	3	28	8	34	15.78	170	20.82	277
4387	SUPRA 0.5 N2+20 I3 F PE 25KG*40 GPE	5SLOW	5REST	3	28	3	86	29.81	165	26.06	469
5331	COLRUYT F PP 1KG*12 WR*96 LWEF	6FAST	5REST	3	28	3	103	24.61	157	16.91	507
3588	BROXO 6-15 PE 10KG*99 EHEF 990	SFAST	SFAST	2	1	8	66	15.07	156	14.71	594
4385	AN IND UNS PE 25KG*40 EHEF 1000	5SLOW	5REST	3	28	4	87	21.80	155	20.09	421
5071	PDV ZOUT25KG*49 NHIF 1225	5FAST	5REST	4	30	4	43	21.23	150	35.96	342
8019017	KNZ LICK UNIVERSAL 25KG*45 EHEF 112	SFAST	SFAST	4	1	1	76	0.00	150	175.69	266
8019004	KNZ LICK FERTILITY 10KG*140 NHLF 14	5SLOW	5REST	4	30	3	87	2.83	145	40.40	413
8019954	NEZO QATAR I F PP 1KG*12 WR*120 NHIF.	6SLOW	5REST	3	22	1	100	0.00	132		200
4404	SUPRA 20 I3 F PE 25KG*40 GPEF 1000	5FAST	5REST	3	28	5	92	4.12	131	14.59	679
8019955	NEZO QATAR I F PP 1KG*12 WR*105 NHIF	6SLOW	5REST	4	30	1	100	0.00	129		200
Total				904		465	85	64.26	50	18.97	54580

Figure 55: BI tool allocation per product

G.4 Other BI-tools

During the graduation assignment, we implemented a few other BI-tools unrelated to our research. These are discussed below.

G.4.1 Replenishment movements

Often locations with the same product and the same batch can often be aggregated towards 1 storage location. This is called replenishment, this tool shows which locations can be aggregated.
Additionally, free locations are shown as well as the utilization of each bulk location.

MAGAZIJN-BEZETTING

Kies zone: All

Kies artikel: All

11.58K
Aantal pallets in de bulk

VRIJE LOKATIES:

117	149	154	169	170	241	246	300	535	542	546	547	553

Bezetting: vloer-lokaties

Magnr.	Lokatie	Artikel - Batch	Gewicht	SH	SH-controle	Aantal	Capaciteit	Bezetting	Opslagdagen	Samenvoegen	Vandaag Uit
5	251	8020447-1896544	1152	3		36	52	69 %	3		
5	114	8020447-1896544	1152	3		64	58	110 %	4		
6	556	8020447-1893408	1152	3		50	66	76 %	35		
5	301 A	8020278-1889821	1270	3		7	10	120 %	38		
5	121	8020277-1894054	1088	3		22	28	79 %	8		
5	139	8020277-1894054	1088	3		13	28	46 %	7		
5	240	8020277-1894054	1088	3		62	64	97 %	9		
5	168	8019973-1891487	1200	4		35	34	103 %	62		
4	420	8019969-1899686	1360	4		40	70	57 %	1		
5	202 C	8019968-1909149	1360	4		7	15	47 %	6		
4	452	8019968-1906034	1360	4		60	70	86 %	7		
6	509	8019967-1902087	1400	4		62	72	86 %	14		
5	135	8019967-1898124	1400	4		17	38	45 %	28		
5	151	8019967-1898124	1400	4		38	38	100 %	28		
4	442	8019967-1898124	1400	4		70	70	100 %	28		
4	405	8019967-1898122	1400	4		63	70	90 %	28		
4	445	8019967-1893169	1400	4		53	70	76 %	29		23

Figure 56: BI tool replenishment

G.4.2 Pallet in wrong storage zone

We also show which pallets are stored in the wrong storage zone. These pallets can either be moved towards the correct zone, the pallet racks or they can stay at their current location.

Overzicht zonevreemd

Pallets per product in elke zone (Leeg = stelling/Akzo)

Locatieklasse		4EXP	5FAST	5REST	5SLOW	6FAST	6SLOW	Total
4EXP	255	1649	142	94	300	58	179	**2677**
5FAST	226		2122	71	1160	614	596	**4789**
5SLOW	347	173	490	170	568		227	**1975**
6FAST	99	111	170	60	269	301	159	**1169**
6SLOW	111	346	36	17	73	32	157	**772**
Total	**1038**	**2279**	**2960**	**412**	**2370**	**1005**	**1318**	**11382**

Vakken per product in elke zone (Leeg = stelling/Akzo)

Locatieklasse		4EXP	5FAST	5REST	5SLOW	6FAST	6SLOW	Total
4EXP	8	32	3	4	8	1	4	**59**
5FAST	5		38	3	24	8	14	**92**
5SLOW	11	4	9	6	15		5	**50**
6FAST	2	2	4	3	5	4	4	**24**
6SLOW		6	1	1	2	1	3	**14**
Total	**20**	**44**	**55**	**17**	**54**	**14**	**30**	**230**

Vakken bezet per zone

Zone	Vakken bezet met producten uit deze zone	Capaciteit zone
4EXP	56	50
5FAST	92	72
5SLOW	47	62
6FAST	24	15
6SLOW	14	45
SFAST	26	
SSLOW	20	
Total	**270**	

Vakken bezet per product

artnr	loknr	magnr	Aantal
3059	523	6	44
3082	110	7	17
3082	412	7	13
3181	102	7	9
3181	109	7	24
3181	112	7	24
3181	406	7	24
3567	303	5	53
3567	439	4	58
3567	443	4	42
3569	106	7	1
3569	107	7	26
3569	108	7	11
3569	408	7	12
3588	101	5	12
3588	104	5	40
Total			**12897**

Figure 57: BI tool pallets in wrong zone

G.4.3 Inbound product overview

We also show the number of pallets inbound destined for the bulk storage locations and the pallet rack system per hour. With this overview, planners can manage the influx towards the pallet rack system, as this influx can create a bottleneck.

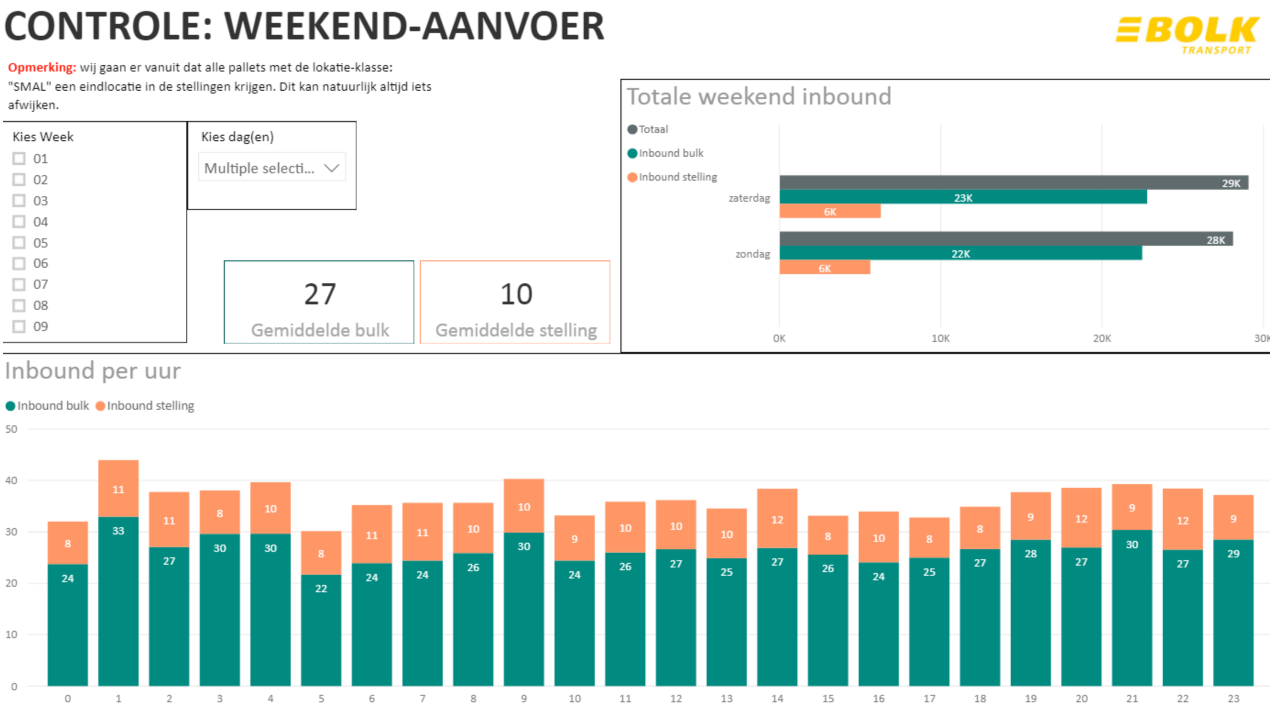

Figure 58: BI tool inbound pallets per hour

H. Screenshot simulation model

The simulation model represents the outbound flow of the warehouse. All fourteen outbound docks are modeled with 3 entities. First, a machine for picking, followed by a buffer and a machine for loading. Both machines are coupled to a workspace.

The picking and loading machine read the respective picking and loading time for a ride. The machines can only start when a worker is present at the work station, the workers are thus the bottleneck in our model. Rides wait in the buffer until their carrier arrives.

When a ride is released for picking, i.e. send to the picking machine, is determined by the current policy.