MASTER

The influence of dynamic carrier-to sortation-lane allocation on the performance of an e-commerce warehouse, in a wave-based pick environment

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The influence of dynamic carrier-to sortation-lane allocation on the performance of an e-commerce warehouse, in a wave-based pick environment

Master Thesis

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Abstract

The E-commerce business is developing rapidly, customers are increasingly buying their goods online instead of visiting a physical store and expect fast delivery. Therefore, e-commerce retailers are continuously searching for optimizations of their warehouse and transportation processes. This research focusses on the sortation operation of an e-commerce warehouse with a wave order release strategy and many outbound carriers. The sortation process consists of an automatic conveyor system, which sorts the parcels based on the delivery carrier. The sortation system consists of two types of lanes, external and internal sortation lanes. External lanes are preferred as the handling costs are lower. Sortation lanes can be allocated to a different carrier in a different wave, however the wave release strategy causes that the arrival of orders of different waves at the sortation system overlap. This study investigates the effects of a dynamic carrier-to-lane allocation on the performance of the parcel sortation, taking into account the overlapping arrival of waves. A mixed integer quadratic programming (MIQP) model has been developed to allocate carriers to a sortation lane dynamically. The stochastic throughput time of order picking is modeled with a probability distribution and used in a heuristic to compute the system boundaries of the dynamic allocation model to deal with the wave overlap. A simulation model has been developed to test the actual performance of the model. The application of the dynamic allocation model in a case study shows that the dynamic carrier-to-lane allocation model can reduce the number of orders processed on an internal sortation lane and thereby reduce the handling costs. However, a reduction in the handling costs can only be achieved when there is no or only a minimal overlap between the sortation of waves. If no overlap in the sortation of waves exists, the dynamic carrier-to-lane allocation model performs best when it is reviewed every day. As it is difficult and costly to reduce the overlap in the sortation of different waves, it is suggested to perform a static wave allocation for a longer planning horizon.

Management summary

This report is part of a master thesis project conducted in cooperation with vidaXL. vidaXL is a Dutch e-commerce retailer, which sells slow moving consumer goods for in and around the house. The research focuses only on the European operations of vidaXL executed from Venlo. This management summary provides an overview of the most important research outcomes.

Problem context

This research focuses on the parcel sortation process of a rapidly growing e-commerce retailer (vidaXL). With the increasing number of sales, the expansion of countries in which vidaXL is active and the increase of transport partners (carriers), there is a need to allocate carriers in a more efficient way to the sortation process.

The sortation process of vidaXL consists of an automatic conveyor system, which sorts the parcels based on the delivery carrier. The sortation system consists of two types of lanes, external and internal sortation lanes. In the external section, parcels can be directly loaded into the trailer of the carrier. The internal sortation lanes require additional process steps which result in higher handling times and costs compared to the external sortation lane. However, only a limited number of external sortation lanes are available. vidaXL uses a wave-based pick and batch policy to release pick tasks. Many orders are released at once to all different warehouse areas, all pickers receive a list of picks in a specific area. Afterwards, when a picker completed a pick round, the orders are loaded on the sortation system. Sortation starts and orders consisting of more picks are bundled.

During each wave carriers can be allocated to another wave, but currently, the carrier to sortation lane allocation hardly differs between the waves. This does not make it possible to schedule a high volume of a carrier on a lane during the first wave and a high volume of orders of another carrier during the second wave. Furthermore, the carrier to sortation lane allocation is fixed for a long period (e.g., months). Moreover, the sortation process overlaps as a new wave already starts before the first one is ready, which makes the decision when to change carriers to a lane even more complex.

Therefore, it is interesting to investigate whether it is possible to develop a more dynamic sortation policy, resulting in a more efficient carrier-to-lane allocation and order batch creation decisions and ultimately reduce handling costs. All in all, this results, in the main research question:

“How does a dynamic carrier to sortation lane allocation, influence the performance of a manual picker-to-parts e-commerce warehouse, with a wave order release strategy?”

Research design

To answer the research question, first of all an in depth analysis was executed. This analysis showed that potentially the most benefit can be achieved by switching lanes between carriers during the day. First of all, a literature review was conducted to investigate possible modeling approaches and the design requirements were defined.

Ultimately, a solution was designed that minimizes the additional handling costs for the internal sortation lane by allowing to allocate carriers to different waves during the day. To do so, it was decided to develop a dynamic carrier-to-lane allocation model, using a mixed integer quadratic programing (MIQP) approach.

To deal with the stochastic throughput time of order picking in the warehouse and the overlapping arrival at the sortation lanes of both waves, system boundaries were set in the MIQP so that at least a minimum percentage of orders are sorted according to the carrier-to-lane allocation of the MIQP. A heuristic was developed to determine the system boundaries, the release time of a wave and the carrier to lane change time between two waves. To compare the performance of the dynamic allocation in the actual situation a simulation model was developed. Lastly, to test the performance of the dynamic allocation model a case study was executed on different types of days.

Results

From the case study it appears that the dynamic lane allocation model results in a reduction of the usage of the internal sortation lane compared to a static lane allocation. A dynamic carrier-to-lane allocation can theoretically result in a reduction of 16 to 40 hours handling time a day depending on the number of orders. However, the relative reduction in handling time will decrease when the number of orders increases. The actual performance of the dynamic carrier-to-lane allocation, tested through simulation, shows overall the same or worse performance than the static lane allocation. Mainly caused due to the overlap in sortation of the different waves.

Results of reviewing the dynamic carrier-to-lane allocation on different time horizons, shows that reviewing the carrier-to-lane allocation daily reduces the number of sortation lane changes between the waves. Which reduces complexity during the day. Moreover, reviewing the dynamic carrier-to-lane allocation daily or twice a day, will reduce the number of orders sorted on the internal lane compared to reviewing weekly or monthly. However, the actual performance shows only a reduction in the number of orders sorted on the internal sortation lane when reviewing twice a day compared to weekly review, also mainly caused by the overlap in sortation of the different waves.

Lastly the results show the influence of changing the percentage of orders sorted in the required wave on the number of orders that can be handled in a day. Minimizing the overlap in wave arrival by releasing the next wave on a later moment is not reasonable as it would decrease the total capacity heavily. Therefore, it would be interesting to investigate other methods to separate the sortation of the waves.

Conclusion and recommendations

Overall, a dynamic carrier-to-lane allocation method in a warehouse with a wave order release strategy, can reduce the number of orders processed on an internal sortation lane and thereby reduce the handling costs. However, this is only the case when the sortation of waves do not overlap or the wave overlap is minimized. In the current situation of vidaXL, with overlapping waves, a static wave allocation model performs better. Therefore the following recommendations are defined:

As long as the wave overlap cannot be reduced keep using a static carrier-to-lane allocation model. Furthermore, the benefits for introducing a dynamic carrier to lane allocation updated daily are low. However, the effect on the number of lane changes is high, which cause complexity. An additional investigation should be done to see which investments are needed to handle the complexity of the lane changes.

Investigate methods to reduce the overlap in the sortation of waves. In the current situation it is not recommended to change the carrier-to-lane allocation and introduce a dynamic carrier-to-lane allocation. However, the current almost static carrier-to-lane allocation also contains a few lane changes. Therefore, it would be beneficial to find ways to split the sortation of the waves. Otherwise the effect of the few planned changes will be lost. Furthermore, more orders that have a due date just after a wave end will arrive before the departure of the carrier truck.

When using a carrier-to-lane allocation for a fixed period, determine at the start of each day with the use of the available order information, whether a planned carrier-to-lane change is beneficial. This can reduce the number of changes during a day. Furthermore, only execute changes with a benefit above a minimum volume.

Preface

This master thesis report is the result of my graduation project for the master Operations Management and Logistics at Eindhoven University of Technology. The project investigates the dynamic allocation of carriers to sortation lanes in an outbound e-commerce warehouse. The master thesis project has been conducted at vidaXL and supervised by dr.ir. Rob Broekmeulen and dr. Vinh Dang from of the Eindhoven University of Technology and Erik van der Hooft of vidaXL.

First of all, I would like to thank my first supervisor of the TU/e, Rob Broekmeulen, for his continuous support and guidance during the master thesis project. Thank you for the interesting discussions, ideas and motivational conversations when needed. Above all, you were always willing to discuss and offer support. I admire your enthusiasm, knowledge and interest in the retail and warehousing environment, what contributed to my interest in warehousing and retail before and during this master thesis project. I would also like to thank my second supervisor, Vinh Dang, for his feedback and critical view. Your feedback has helped me to improve the quality of the research.

Secondly, I would like to thank vidaXL for the opportunity to conduct my research and their ongoing support. In particular, I would like to thank Erik van der Hooft for his guidance during the project. Your ideas, feedback and support are greatly appreciated. I admire your enthusiasm in the field of supply chain, which was evident when discussing design and research ideas during our weekly meetings. Furthermore, I want to thank Jonne Kasje for his input and interest in the operational part of the research. I would also like to thank the supply chain solution and control team for their help during the project and the effort to make me feel part of the team. Finally, I would like to thank all the people of vidaXL for all the help and answered questions during the project.

And last but not least, I would like to thank all my friends and family for their unconditional support during the project. A special thank you to my parents who have always supported and believed in me during my study period. For my family and me, the period in which I conducted my master thesis was quite heavy. I owe a lot to all the support I received from family and friends during this period, which ultimately contributed to the delivery of this master thesis report.

Bart Hermkens
Eindhoven, November 2022

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BPMN	Business Process Model and Notation
MIP	Mixed integer programing
MIQP	Mixed integer quadratic programing
MILP	Mixed integer linear programing
FIFO	First in first out

1. Introduction

In this first chapter, the project environment in which the research is conducted is introduced. First, some background information about the practical problem of the company is given. The problem description is discussed, and the research objective and questions are defined. Thereafter, the research design is defined. Furthermore, the report structure is discussed.

1.1. Introduction

The E-commerce business is developing rapidly, customers are increasingly buying their goods online instead of visiting a physical store and are expecting fast delivery (Boysen, de Koster, et al., 2019). Secondly, storage space is expensive, and companies want to use it as efficiently as possible (Bartholdi & Hackman, 2019). Thirdly, freight volumes are increasing (Boysen, Briskorn, et al., 2019). Lastly, labor to process inbound and outbound orders is costly (Bartholdi & Hackman, 2019) and the labor market is currently quite tight (EU, 2022). Therefore, e-commerce retailers are continuously searching for optimizations of their warehouse and transport processes. This research will focus on the parcel sortation process of a rapidly growing e-commerce retailer (vidaXL). With the increasing number of sales, the expansion of countries in which vidaXL is active and the increase of transport partners (carriers), there is a need to allocate carriers in a more efficient way to the sortation process.

This research mainly contributes to the literature by developing a dynamic carrier to sortation lane allocation model, using mixed integer quadratic programming (MIQP) in a picker-to-part warehouse with a wave-based pick environment. While existing research mainly focuses on allocating orders to sortation lanes to bundle all parts of the order or focuses on the allocation of carriers to sortation lanes in cross-dock warehouse so that the inbound and outbound flows are matched. Furthermore, this research contributes with the development of a simple heuristic that determines the system boundaries of a pick-wave, such that an MIQP model can be applied in an environment with stochastic order arrival and overlap in the sortation of waves.

1.2. Company background

This research is executed at vidaXL, a rapidly growing online retailer, mostly selling slow-moving consumer goods for in and around the house. vidaXL strives to offer good quality products for a competitive price, by controlling the whole supply chain from production to shipping. The assortment consists of more than 80,000 products. Most products are from their own vidaXL brand, but some A-brand products are also sold. Products are sold in 32 European countries, the United Arab Emirates, Australia, and the United States. The vidaXL branded products are manufactured mainly in Asia in around 1000 factories. Customers are served from warehouses in the Netherlands, Poland, the United Arab Emirates, Australia, and the United States. The total warehouse space worldwide is more than 700,000 m^2 and new warehouses are planned. From the distribution centers products are transported to regional distribution hubs of their delivery partners. This research focuses on the European operations of three vidaXL warehouses (JTS1, JTS2, and MKI) in the Netherlands located in Venlo (in total 250,000 m^2).

1.3. Outbound process

In this section, the outbound supply chain of vidaXL is discussed. The outbound process starts with receiving the customer order, afterwards, the order should be picked. After picking, if an order consists of multiple parcels, the parcels are bundled in the memory lane section or in the packing section depending on the characteristics of the parcels. Afterwards, the orders are sorted and delivered to the customer.

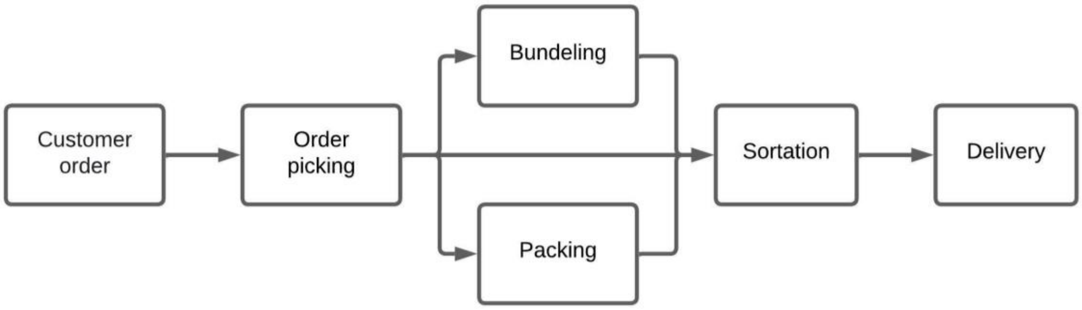

Figure 1: Outbound process vidaXL

Order picking

Order picking is done using a wave-based policy. The wave picking principle consists of gathering customer orders and releasing them at once in large batches to the order pickers. The wave is released at once over all the warehouses. Each picker will receives a list of picks that the picker should pick during the wave. The warehouse has different sections with different layouts and pick methods. Products are stored based on their characteristics. Product characteristics are for example, size, weight and run rate (the average number of times a product is sold during a day). Each section has a different pick method. The **pick-to-train method** is used in the normal aisles, a vehicle with a picker drives through the warehouse and products are only picked on the first level. The other levels are used to replenish to the first level. The pick-to-train method is used for normal moving goods. The **man-up pick method** is used in the narrow aisles, the picker can pick on every storage level with a man-up truck. The man-up pick method is used for slow-moving goods. The **pick-to-belt** area is designed for fast-moving goods, a conveyor belt is located between the storage locations, the picker can pick the parcel and put it directly on the conveyor. The conveyor transports the parcel directly to the sortation area. If for a product more than a pallet quantity should be picked, a full **pallet pick** is executed. The pick-to-train pickers, the man-up pickers, and the pallet pickers deliver their parcels to the train station in the outbound warehouse, where the parcels are put on the conveyor sortation system. Products that are not conveyable due to their size are picked separately and sorted manually.

Sortation

For the sortation and transport of parcels through the warehouse, a conveyor system is used. vidaXL uses one of the three warehouses as an outbound warehouse, parcels of the other warehouses are cross-docked to the outbound warehouse. During the duration of this research, the outbound warehouse is switched from MKI to JTS2. The MKI situation is visualized in figure 2 and the JTS1&2 situation is visualized in figure 3. In both situations, the sortation process works as follows. At the train station, the parcels picked by train, picked in the narrow aisles, and the parcels picked in the other warehouses (cross docks) are put on the conveyer belt. In case a parcel should be bundled with another it is sent via the memory lane, if not it will directly go to the assigned sortation lane or package station. A sortation lane is the end destination of the parcel in the sortation system. There are two different sortation lanes, an external lane is connected with a dock door, which makes it possible to directly load the parcels in the trailer of the delivery partner, with the use of a telescopic belt conveyor, the worker(s) only needs to take the parcel from the belt and stack it into the trailer. Internal lanes are not connected to a dock door and parcels should first be stored in a container or stacked on a pallet before being loaded on a truck. For each external lane, there is also a backup lane available in case the external lane is full, or the truck needs to be changed. The backup lane is working in the same way as the internal lane. External lanes are reserved for destinations with high volumes and internal lanes are reserved for destinations with low volumes or for destinations that require stacking of the parcels on pallets. A schedule is made which destination is assigned to which lane per wave on which day (carrier to sortation lane allocation).

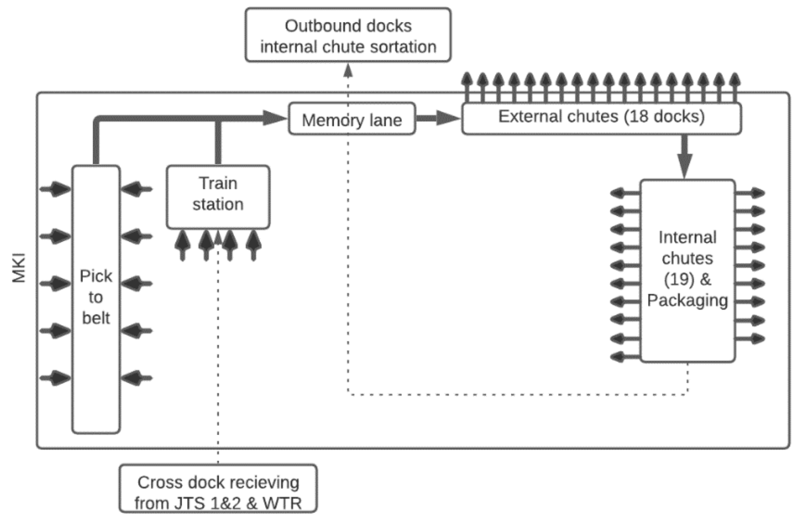

Figure 2: Outbound warehouse MKI

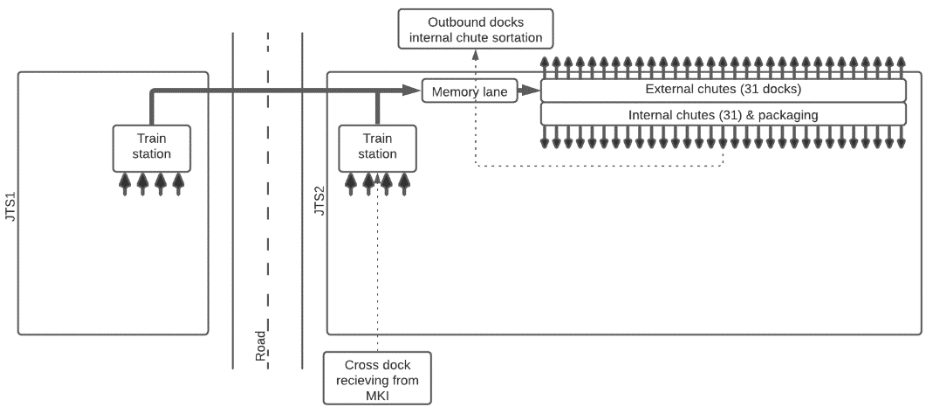

Figure 3: Outbound warehouse JTS1 & JTS2

Wave policy

To determine which orders have to be picked in which wave the transportation planning is used. Orders from carriers with the earliest departure time (earliest due date (EDD)) are scheduled in the earliest wave. Based on the carrier truck departure times (transport planning), the expected number of parcels per carrier, sortation lane capacity and the total conveyor capacity, carriers are allocated to a specific sortation lane with a capacity per wave (carrier to sortation lane allocation). The carrier to sortation lane allocation is per wave, which allows the carrier to change lanes between waves. Based on the carrier to sortation lane allocation and the available customer orders, the wave batch is created. The wave batch is released in pick tasks to the order-pickers.

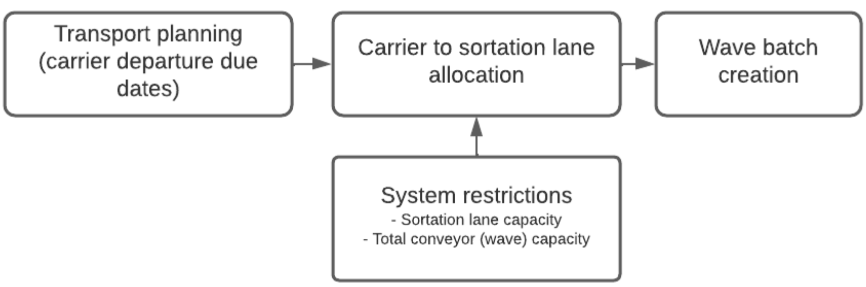

Figure 4: Wave batch creation

1.4. Problem definition

This research finds its motivation in the interest of vidaXL to discover a more dynamic sortation policy in combination with a gap in the literature related to this question. vidaXL has rapidly grown over the last couple of years and future growth is still expected, therefore warehouse functionalities and capacity are upgraded continuously. To make future growth possible, processes have to become more efficient, and costs should be minimized.

Currently, vidaXL uses a wave-based pick and batch policy to release pick tasks in the warehouses (explained in section 1.3). Currently, this process includes many human decisions of planners. Furthermore, the carrier to sortation lane allocation is fixed for a long period (e.g., months).

The sortation system consists of two types of lanes, external and internal sortation lanes. In the external section, parcels can be directly loaded into the trailer of the carrier. The internal sortation lanes require additional process steps which result in a higher handling time compared to the external sortation lane. However, a limited number of external sortation lanes are available. Therefore, it is preferable to schedule the highest volume on the external sortation section as efficiently as possible. Moreover, currently, the carrier to sortation lane allocation hardly differs between the waves, nearly changes from internal to external lanes are allowed. This, does not make it possible to schedule a high volume of a carrier on a lane during the first wave and a high volume of orders of another carrier during the second wave on the same lane. Secondly, the fixed sortation lane allocation does not allow for changes when the volume of a carrier planned on an internal lane is higher than the volume of a carrier planned on an external lane. Thirdly, the expected growth in sales and the expansion of countries in which vidaXL is active, will result in additional carriers and extra volume for the current carriers that all should be allocated to a sortation lane during the day. Moreover, the sortation process overlaps as a new wave already starts as soon as the first wave is ready, which makes the decision when to change carriers to a lane even more complex. Therefore, it is interesting to research whether it is possible to develop a more dynamic sortation policy model, which results in a more efficient carrier-to-lane allocation and order batch creation decisions and eventually reduce costs. With a more dynamic policy is meant, firstly to plan more carrier-to-lane changes in a day and secondly to reduce the planning horizon (e.g. plan at a certain moment for a certain planning horizon).

A more dynamic sortation policy can cause an increase in complexity on the work floor. When, for example, carriers are allocated to another sortation lane every wave and or day it is no longer possible for workers to learn the topography of carrier-to-lane allocation (Zenker & Boysen, 2018). Therefore, it is important to determine the determine what cost and complexity increases are associated with dynamic allocation of carrier-to-lanes to waves and are associated with different planning horizon, (e.g., daily, weekly, monthly changing the carrier to wave allocation policy).

Overall, the current sortation policy is fixed for a long period and no tools or models are available to assist planners. For vidaXL, it is unclear how the carrier-to-lane allocation can be made more dynamic and what the effects are of a dynamic carrier-to-lane allocation. This results in the following research objectives:

- Develop a model that can determine the carrier-to-lane allocation per wave while minimizing the handling costs or time.
- Determine the effect of different planning horizons on the performance of the planning.

1.5. Research questions

To make a structured analysis of the problem described in section 1.4, research questions are formulated. The main research question is divided into several sub-research questions. The sub-research questions will serve as a guideline to answer the main research question and therewith provide a solution for the problem. The main research question is defined as follows:

How does a dynamic carrier to sortation lane allocation, influence the performance of a manual picker-to-parts e-commerce warehouse, with a wave order release strategy?

To answer the main research question, several sub-research questions are defined. The first research question is set to investigate what possible solution designs can be used to develop a model for the carrier to sortation lane allocation.

SQ.1: What are suitable solution designs to allocate carriers to sortation lanes?

The second research question is used to investigate the current performance measures of vidaXL. Subsequently, the second sub-question comprehends the current design and performance of the sortation process of vidaXL. A detailed analysis is performed by discussions with different managers, planners, and warehouse supervisors and by data output of the warehouse management system.

SQ2: How is the current sortation process of vidaXL designed and how does it perform?

The third research question deals with the translation of the problem to a mathematical allocation model. It explores how carriers can be allocated more dynamically (allowing changes) to lanes and waves with the use of mathematical model when considering the system constraints and while minimizing the handling costs. Furthermore, a simulation model is being developed to see how model parameters should be set to deal with stochastic throughput times.

SQ.3: What kind of model can be developed to determine the carrier-to-lane allocation per wave, while minimizing the sortation handling costs?

The fourth and fifth research question deal with the performance of the proposed model. The fifth question deals with the overall performance of the model, how does the model that allow more lane changes during the day perform. The fifth question will deal with the question in which planning horizon the model could be best used (e.g., daily, weekly, monthly).

SQ.4: What are the effects on the warehouse performance for a more dynamic carrier to sortation lane allocation model?

SQ.5: What is the most cost-effective and user-friendly planning horizon of the carrier-to-lane allocation model to increase the performance of the sortation process?

1.6. Research methodology

The goal of this master thesis project is to find a solution for the carrier to sortation lane allocation problem vidaXL is experiencing. To structure the problem, analysis and solution direction, the problem-solving approach is based on the model of Mitroff et al. (1974) (figure 5). Because it is a structured method to develop a scientific solution that can result in a solution to the defined problem. In this model, the research is divided into four phases, namely, (1) conceptualization, (2) modeling, (3) model solving, and (4) implementation. Each phase has a start and end point defined as (I) reality and problem situation, (II) conceptual model, (III) detailed model, and (IV) solution. How this model will be used to solve the carrier to sortation lane allocation problem of vidaXL is discussed shortly in the following subparagraphs.

Reality and problem situation

The problem situation is already discussed broadly in the introduction chapter, to provide more insight into the current process. In addition, some data analysis is executed and discussions with managers and workers on the floor took place to get more insight into the way of working. Furthermore, the current performance indicators are discussed and analyzed. The results of this phase will answer the second sub-research questions.

Conceptual model

In the second phase, a conceptual model will be modeled. To define the conceptual model the problem situation and data analysis are considered. Furthermore, a literature study is executed to see what the possible solution directions are. A list of model requirements and constraints is defined. The results of this phase will answer the first and partly the third sub-research question.

Detailed model

In this phase, also called the scientific model, the mathematical model, system boundaries and simulation model are defined. The mathematical model is based on mixed integer quadratic programming (MIQP). This is a way of modeling in which the objective consists of multiple variables that are multiplied by each other. The variables are constrained by linear constraints. The mathematical model provides a carrier-to-lane allocation per wave. Moreover, a heuristic is developed to determine the system boundaries of the mathematical model (e.g., set parameters such as the wave release time and wave capacity). Furthermore, a simulation model is used to test the system performance of the carrier-to-lane allocation. This will answer sub-research question three.

Solution

In the solution phase, the performance of the detailed dynamic carrier-to-lane allocation model will be compared to a static allocation model. Several scenarios are defined for the different input parameters (e.g., number of orders, and number of working shifts). The simulation model is used to verify the performance of the model in a similar situation. All in all, this will result in an answer to sub-research question four.

Next to this, it is investigated what the most ideal planning horizon is to review the dynamic carrier-to-lane allocation model. All in all, this will result in an answer to sub-research question five.

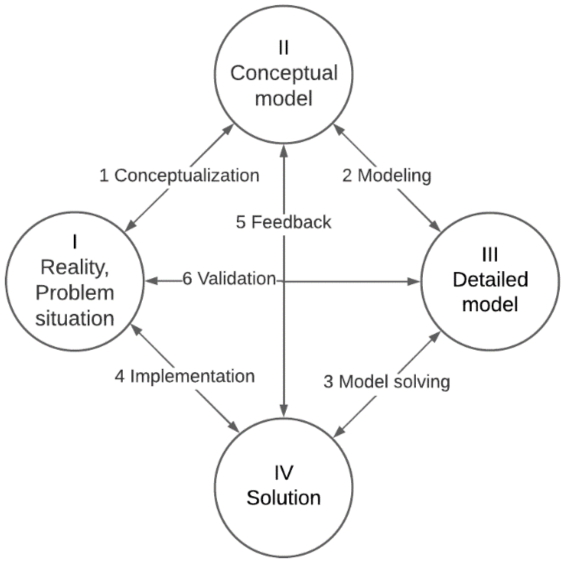

Figure 5: Research phases (Mitroff et al., 1974)

1.7. Scope of research

The scope of this research will be limited to the outbound operations associated with the sortation process of vidaXL in Venlo, the Netherlands. The focus will be on the allocation of carriers and orders to lanes and waves, this includes wave duration, number of waves, wave capacity, wave batch creation (orders to wave), and carrier-to-lane allocation. All these processes will also influence other processes in the warehouse, for example, the picking of parcels depends on the wave batch creation. Furthermore, the accuracy of a forecast can influence the carrier-to-lane allocation. However, as the focus is on the carrier-to-lane allocation during each wave and limited time is available for the research it was necessary to make assumptions about processes that are outside the main process. As long as it represents reality accurately, this simplifies the design and decreases computation time.

vidaXL has different types of products that can be distinguished into products that can be automatically sorted (conveyable products) and products that cannot (non-conveyable products). Only conveyable products are in the scope of this research as they represent 90 to 95 percent of the sales. Moreover, the non-conveyable products require special handling and therefore follow other processes. Furthermore, the non-conveyable products are often carried with other delivery partners (carriers) or are picked based on the carrier-to-lane allocation of the conveyable products.

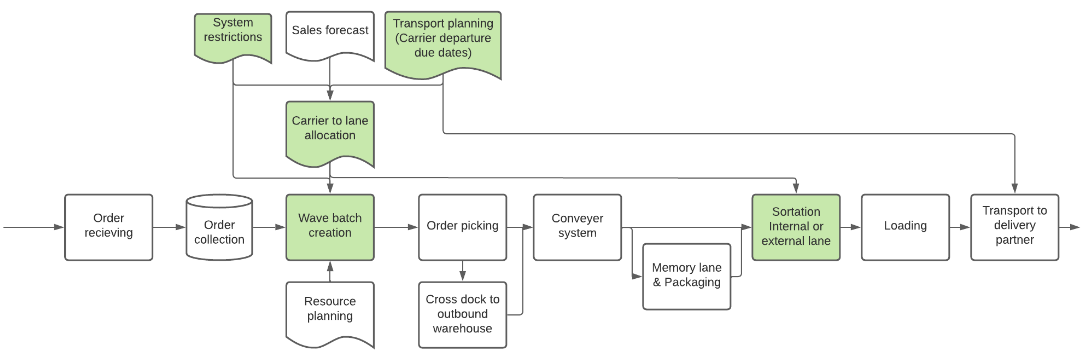

Figure 6: Process overview of order fulfillment

1.8. Outline report

In the remainder of this report, the research executed is further described. Chapter 2 will discuss literature about allocation policies and warehouse sortation systems. Chapter 3 discusses in more detail the process of vidaXL and further diagnoses the bottlenecks in the process by analyzing data of the warehouse management system. Chapter 4 will present the conceptual design in which the requirements for the detailed design are listed. Chapter 5 discusses the detailed design; the mathematical model, system boundaries and simulation model is presented. In chapter 6 the setup and research scenarios of the case study are discussed. The results of the case study are presented and discussed in chapter 7. Finally, in chapter 8 the conclusions and recommendations are discussed.

2. Literature study

This chapter shortly summarizes the literature available on the elements, methods, and objectives concerning optimal scheduling of outbound operations. In preparation for this research, an extensive literature review on warehouse truck allocation has been carried out (Hermkens, 2022). The main fields discussed are e-commerce warehouses, automating sortation systems, wave picking and allocation policies. The last section summarizes the findings and identifies the research gaps within this topic. Furthermore, the academic relevance of this study is pointed out.

2.1. Fixed or dynamic allocation and planning horizon

Fixed allocation allocates a destination for a long period of time to a fixed dock door or sortation lane (Zenker & Boysen, 2018). This method is often applied when outbound destinations are served often (e.g., multiple trucks a day) (Boysen & Fliedner, 2010). Fixed assignments reduce complexity and create more reliable processes, it allows workers to learn the topography and the information systems of the terminal (Boysen, de Koster, et al., 2019; Boysen & Fliedner, 2010; Fedtke & Boysen, 2017; Zenker & Boysen, 2018). In contrast, a fixed allocation of destinations to a dock or sortation lane restricts the degrees of freedom for short-term assignment (e.g., a peak volume cannot be absorbed by an additional lane or dock). Therefore, fixed allocation is often used for steady commodity flows with a reliable distribution between destinations (Boysen & Fliedner, 2010). Moreover, a fixed allocation also has a negative influence on the utilization of the dock door (Boysen et al., 2010). Whether a fixed allocation is possible also depends on the number of available lanes or docks. When the number of outbound destinations is higher than the total number of lanes, it is not possible to make a fixed allocation and a more short-term (dynamic) allocation should be applied (Boysen, Briskorn, et al., 2019). Overall, the lane or door allocation problem tends to become more complicated when the number of different carriers or trucks exceeds the number of docks available at the warehouse (Shuib & Fatthi, 2012).

Also, the planning horizon can differ. An allocation of a sortation lane to a dock can be fixed for a long period, or the planning can, for example, be determined every day or even every hour (Boysen et al., 2010; Fedtke & Boysen, 2017; Nassief et al., 2016). The time horizon, that is used to solve the problem, also depends on how much information about the operations is available upfront, for example, order information and carrier arrival and departure time (Boysen et al., 2013; Gu et al., 2007).

2.2. Wave picking

In a picker-to-parts warehouse, different pick methods can be divided in pick by order, pick only one order per time and in batch picking, picking multiple customer orders by article (Charles & Petersen, 2000; de Koster et al., 2007). The sortation of batches can take place during picking (sort-while-pick) or after picking (pick-and-sort) (Charles & Petersen, 2000; de Koster et al., 2007). Batching can be extended by zoning; the storage areas are logically divided in zones. Pickers are assigned to a zone and will only pick the part of the batch that is stored in the zone.

Wave picking is a special case of batch zone picking where pickers pick very large batches, mostly based on the length of the pick time available, the number of trucks waiting for orders and the capacity of the sortation system (Charles & Petersen, 2000; de Koster et al., 2007; Meller, 1997). The pick time available depends for example on the departure time of carrier(s). During a wave, pickers pick continuously and only pause to unload full picking carts at the sortation area or sortation system. In principle a next pick wave can only start when the previous wave is fully finished (e.g., other destinations trucks should arrive, sortation area should be empty). However, to reduce resources idleness between waves, some companies develop policies and systems to allow waves to overlap

(Gallien & Weber, 2010; Russell, 2001; Russell & Meller, 2003). Systems that allow waves to overlap result in a lower total annual system cost than a system without overlapping waves.

2.3. Automatic sortation system

Some warehouses make use of automatic sortation systems, also called conveyers (Zenker & Boysen, 2018). An automatic sortation system can be used for mainly two purposes in a fulfilment warehouse. Firstly, to merge all picks of an order in one parcel. The sortation lanes are used to accumulate all picks of the order. When all picks are available in the lane, the picks can be packed in one parcel (Russell, 2001). This is known as the order to lane assignment problem (de Koster et al., 2007; Meller, 1997). Another purpose can be to sort parcels for their destination, where each sortation lane is used for a destination (de Koster et al., 2007; Rouwenhorst et al., 2000). This is known as the destination (carrier) to lane assignment problem (Meller, 1997).

Often the wave order picking principle is used in combination with an automatic sortation system. In case of a fulfilment center, the receiving and shipping operations are more complex to manage since they are coupled with the storage and order picking function. The scheduling of shipping trucks may, for example, depend on how many orders are batched and assigned to picking waves and vice versa (Gu et al., 2007).

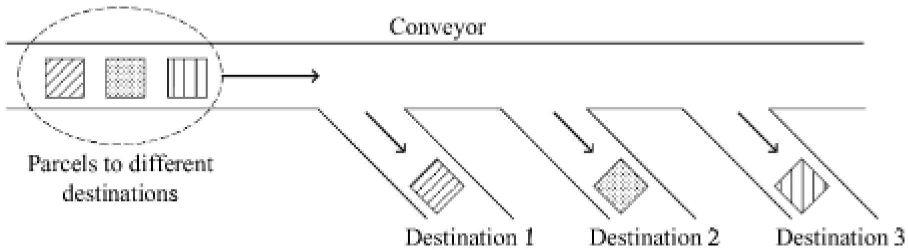

Figure 7: Sortation lanes (Chen et al., 2021)

2.4. Performance measures and objectives

Many objectives are used to reduce the number of late shipments to increase customer satisfaction by increasing on time delivery. Those objectives focus on completion time, lateness, tardiness, or make span. In line with this, minimizing the tardiness of shipments is the most mentioned objective (Ardjmand et al., 2018; Boysen & Fliedner, 2010; Buakum & Wisittipanich, 2019; Henn, 2015; Menéndez et al., 2017; Scholz et al., 2017). Some objectives are more focused on warehouse efficiency, by focusing on the service time of inbound and outbound trucks, inventory, travel distance or handling costs (Buakum & Wisittipanich, 2019; Mavi et al., 2020; Nassief et al., 2016; Shuib & Fatthi, 2012). Another part of the objectives is focusing on creating steady flows through the warehouse to ensure workers have an equal workload, which could result in better work conditions or fewer workers needed for the operation (Jarrah et al., 2016; Shuib & Fatthi, 2012).

2.5. Solution methods

To tackle the sortation lane assignment, batching and the truck to dock allocation problem, several solution methods are used. Often traditional priority rules are used to develop a policy (Fedtke & Boysen, 2017; Kim & Ok, 2008; Meller, 1997). Algorithms or heuristics are often used to improve the solutions of the traditional priority rules. Mixed integer (linear) programing (Jarrah et al., 2016), stochastic modeling (Gong & de Koster, 2011), and queuing theory (Briesemeister & Novaes, 2017) are sometimes used to come to a solution and to obtain an approximation of the performance of the proposed solution. Simulation is often used to test the performance of solution designs and to set or test different parameter settings (Eldemir & Karakaya, 2011; Fedtke & Boysen, 2017).

Many operational characteristics that could be considered when determining the carrier to sortation lane allocation, are uncertain. They are often modeled as a stochastic process, for example, the truck arrival time, departure time, and arrival time (Goodarzi et al., 2022; Jarrah et al., 2016).

In a complex operational outbound situation a heuristic or algorithm can be a suitable design to solve the carrier to dock allocation or the carrier to sortation lane allocation problem. The performance and parameter settings of the heuristic can be tested with a simulation model. In a complex situation with many elements, interactions, uncertainties, and stochastic factors an analytical approach often results in a non-linear model formulation, which increases the model complexity. In comparison with an analytical approach a heuristic in combination with simulation has a lower computation complexity. This allows to add more variables to the model and make less assumptions and thereby fewer simplifications are needed. Also, a heuristic has a lower computation time, which is helpful when a dynamic planning approach is used. Lastly, an analytical approach is more time consuming. On the other hand, an analytical approach results in a better solution. However, if many simplifications are made, it is doubtful how useful such a solution will be in practice. In a less complex situation, an analytical approach can be suitable. For example, mixed integer (linear) programming, stochastic modeling, and queuing theory.

2.6. Research gap

Extensive research is done into the truck-to-dock allocation problem, mostly focusing on cross-dock warehouses, including parcel sortation centers, rather than traditional pick warehouses. In the existing literature about the dock door allocation problem, some attention is paid to the tradeoff between fixed or dynamic scheduling, (operational) complexity, and costs. However, no clear conclusion is drawn or framework is developed to properly balance these three factors when deciding on a truck-to-dock allocation policy.

Furthermore, research is being done into the order-to-lane assignment policies for automatic sortation systems, but less research is executed on the carrier-to-lane allocation policies. Therefore, developing new policies or adjusting existing policies for use in a carrier-to-lane sortation system is necessary. Many different objectives are applied when modelling allocation problems. Within the carrier-to-lane allocation problem, no research is known on sortation lanes with different handling times and the objective to reduce handling times and costs.

Thirdly, the warehouse wave order release policy is discussed in literature, also in combination with automatic sortation systems. However, not much detailed research is carried out on warehouse wave order release with overlapping waves and the effect of this on sortation, truck allocation policy, and other warehouse operations.

3. Analysis and diagnosis

In this chapter, a detailed analysis is provided of the current outbound operation of vidaXL. In the last part of this chapter, a conclusion for further investigations is drawn. For the analysis, warehouse data of the warehouse management system of vidaXL from May 2021 until December 2021 is used. The time period is limited as this was the only historic data that was available at the beginning of this research. However, it was enough data to observe trends in the data and to draw conclusions about performance. Furthermore, it consists of a period of high customer demand (May 2021 until Augustus 2021) and a period of low demand (September 2021 until December 2021). In periods of low demand vidaXL works in a single shift and in periods of high demand in a double shift. Therefore, in the sections below often a distinction is made in the data of a single and double shift. Next to data analysis, information is retrieved from supply chain management, operation managers, and warehouse team leaders during discussions about the outbound process.

3.1. A warehouse workday

As discussed in section 1.3. the warehouse processes can be split into picking and sortation. Both processes are executed in waves. A wave is a batch of orders that are released at once to the order pickers. After the wave is released, no other orders can be added to the wave. The picking and sortation process is executed by two different teams with different working hours. Pickers start and end one hour earlier than the sortation team. In this way, the picking team already ensures that some of the orders are picked such that the sortation team can start directly with the sortation process (figure 8). A workday can consist of one or two working shifts depending on the season. If a high workload is expected during a long period, work will be executed in a double shift. One shift has a duration of nine hours including a one-hour break.

Currently, during a single shift (figure 8), the main workload (number of parcels) is processed in two waves. The waves are spread over the day, the work hours are fixed, which means that the wave batch release and start sortation time of the first wave are fixed, just as the end of picking and end of sortation. However, it can vary when the first wave ends, and when the second wave starts. In addition, the second wave is always released earlier than the end of sortation and picking of the first wave. The workload of the waves can differ. For example the first wave can have a higher workload, which results in a longer duration. During a double shift, currently, work is executed according to a two-wave strategy or sometimes by a four-wave strategy. The same applies as during a single shift, the start times of the first wave and the end times of the last wave are fixed and the wave workload, wave duration, and wave release can vary.

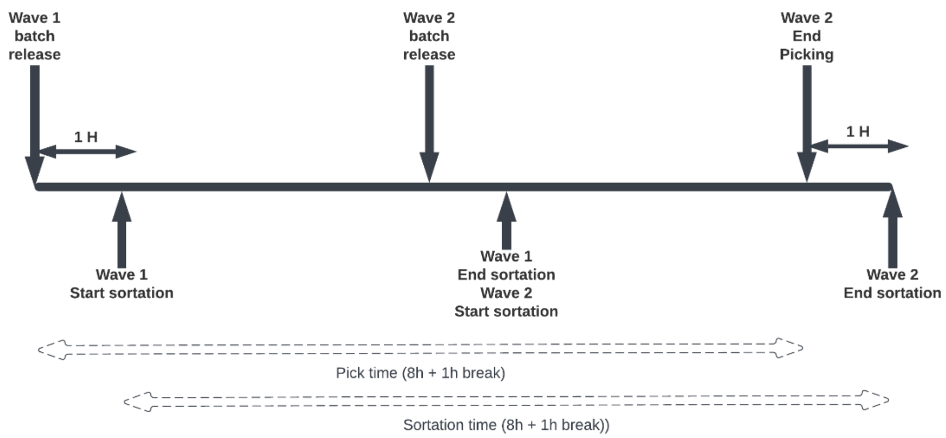

Figure 8: Single shift with two waves

Table 1 shows the distribution of the orders over the different waves. In both single and double shifts, the first wave has on average the highest percentage of orders. This is caused by the transport planning; many orders are planned in the first wave because the carrier they belong to will have a departure during or just after the first wave. Moreover, some carriers will only depart once a day, and when this departure is during or just after the first wave it is necessary to plan all available volumes of this carrier in the first wave. In a single shift, a two-wave scenario is used. However, as can be seen in figures 9 and 10, there is also some volume handled in a third and fourth wave. These waves are additionally released for two reasons. Firstly, to process orders that could not be picked in the first two waves, because the product is not yet available on a pick location and first a replenishment should happen, or the inventory on the pick location is not correct. Secondly, to pick orders that are received during the workday, those orders are only released when the pickers have finished their workload and still have work hours left.

Figures 9 and 10 show an illustration of order arrival during a day at the sortation area during a single and double shift. As can be seen, the arrival of orders at the sorter of the different waves overlap each other. The figures show that as soon as the number of parcels of the first wave reduces also orders of the second wave arrive. The overlap of the waves is needed to provide order pickers with pick tasks. If the waves do not overlap, some order pickers will not have pick tasks during the last part of the wave, as they need to wait for the other order pickers to finish all the picks task, which will result in a less efficient pick operation.

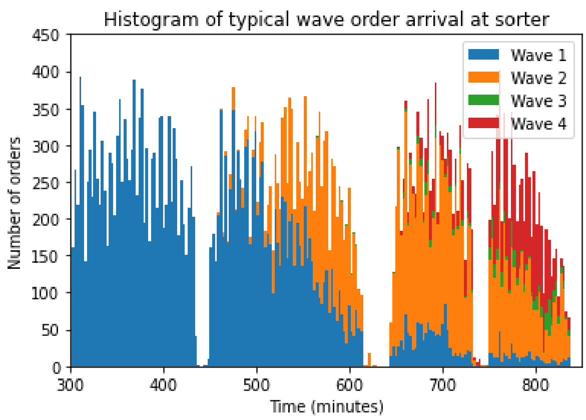

Figure 10: Illustration of order arrival at the sorter during a single shift

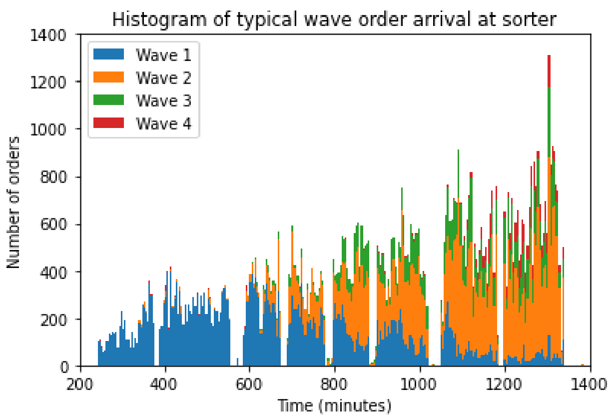

Figure 9: Illustration of order arrival at the sorter during a double shift

The overlap of the waves causes difficulties when a carrier sortation lane change occurs between the waves. Currently, changes are barely planned during the day. But, when a change has to be planned, it is not clear what the best moment is to execute this change. The operation department decides on this when they think most of the volume of the previous wave has been processed. An example is shown in figure 11. Carrier 2 is scheduled in wave 1, while carrier 1 is scheduled during wave 2, the purple area shows the overlap between the arrival of parcels of both carriers. Only one of the carrier's parcels can be sorted to the lane, the parcel of the other carrier should go to an internal sortation lane.

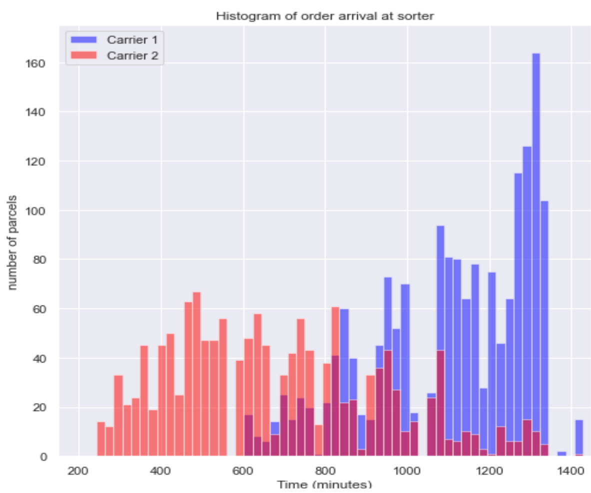

Figure 11: Illustration of parcel arrival at sorter for different carriers

3.2. Outbound performance indicators

In this section, shortly the performance indicators that are relevant for the wave batch creation and carrier-to-lane allocation are discussed. The customer service level is the most important performance measure of vidaXL. The service level is defined as the number of parcels that are processed in the warehouse 24 hours after the time they are available in the warehouse management system. This means that when an order is loaded in a trailer, but the truck does not depart that day, the required service level is still achieved. This means that all orders that are received the previous day should be at least allocated to a wave the next day.

Next to the service level the handling time and costs are important measures. All warehouse areas have a norm that states how many parcels should be processed per work hour. The overall norm for the sortation operation is 140 parcels per working hour. The norm for processing parcels at an external sortation lane is 150 parcels per hour and the norm for processing parcels at an internal sortation lane is 100 parcels per hour. Therefore, the percentage of orders sorted at the external lane and internal lane is also an important measure of performance.

3.3. Outbound order throughput time

A wave is released at once to the warehouse. When the wave is released, the batch is distributed among all the order pickers, and the picker starts collecting the assigned orders. After the picker picking vehicle is full, the picker drops his orders at the sortation train station, where the orders are loaded on the conveyor. The time between the batch release and the arrival of an order at the sortation lane is called the warehouse throughput time of the order. The throughput time includes all processes and waiting times between batch release and sorting.

Throughput time = Arrival time of order at sortation lane – Wave batch release time of order

In Table 1 the average throughput time and standard deviation in minutes for the different routes an order can follow between batch release and sortation can be found. The average is taken in a single shift period, in a double shift period and over both periods.

The different routes related to bundling are defined as follows.

- Non-packing: the box arrives at the sorter and is immediately sorted as it does not require a bundling step.
- Memory lane: an order needs to visit this section when a customer has ordered multiple times the same product. These boxes will be bundled into one parcel. Normally, the boxes that should be bundled arrive around the same time at the memory lane, as they are probably picked at the same location at the same time. Therefore, the throughput time is only a little higher (+/- 20 minutes in a single shift) than orders that do not visit memory lane.
- Packing: an order needs to visit this section when a customer order consists of different products that should be combined for the same customer. As different products are probably picked at different pick locations (or other warehouses) at different times, it can take a long time before the different boxes have all arrived. This results in a higher average throughput time (+/- 140 minutes in a single shift) than orders that do not visit the packing area.

The throughput time also differs per warehouse. In the data used to make this analysis the MKI warehouse was the outbound warehouse. The throughput time of the other warehouses is higher as the parcels need to be cross-docked, and before the cross-dock is executed, first a full truckload of picked boxes should be available. The warehouses JTS1, JTS2, and WTR are located close to each other. This results in an almost equal average throughput time for WTR and JTS1. However, the average throughput time of JTS2 is higher, which can be explained as the volume of parcels of JTS2 is lower.

These data were obtained when JTS2 was not yet fully operational. When JTS2 is fully operational, it is assumed it will behave the same as WTR and JTS1. Furthermore, the throughput time differs per wave, the average throughput time and volume of parcels in a wave decreases from wave 1 to wave 4 in both single and double shifts.

Table 1: Average throughput time in minutes and percentage of orders per process, warehouse, and waves

	Single shift			***Double shifts***			***All***		
	mean	*std*	*%*	*mean*	*Std*	*%*	*mean*	*std*	*%*
All process	256.96	133.94		378.37	228.98		328.50	203.99	
Bundling									
Non-packing	253.66	131.95	95.64%	371.28	226.09	93.22%	322.19	200.46	94.21%
Packing	390.23	143.08	2.10%	562.90	237.26	3.08%	508.38	226.41	2.68%
Memory lane	272.65	144.03	2.26%	403.72	228.40	3.70%	363.08	214.46	3.11%
Warehouses									
MKI	213.69	130.88	46.28%	325.83	228.73	49.88%	281.01	202.61	48.41%
WTR	283.66	125.13	13.19%	422.61	218.59	15.52%	372.01	200.02	14.57%
JTS1	282.76	120.86	30.79%	411.60	212.62	34.61%	360.20	192.13	33.05%
JTS2	304.56	126.84	9.74%	N.A.	N.A.	N.A.	N/R	N/R	N/R
Waves									
Wave 1	287.38	142.78	62.29%	414.31	249.16	44.55%	N/R	N/R	N/R
Wave 2	227.51	99.77	28.78%	413.81	226.01	29.74%	N/R	N/R	N/R
Wave 3	151.66	62.91	4.58%	304.04	164.98	16.63%	N/R	N/R	N/R
Wave 4	127.17	54.33	4.35%	222.15	103.61	9.08%	N/R	N/R	N/R

As Table 1 already suggests there is a relation between the number of parcels and the average throughput time. A Pearson correlation analysis is carried out on the single shift excluding the packing and memory lane data. The results of the double shift and all combined data can be found in Appendix 1. There is a positive correlation *$(r(290) = 0.87, p < 0.01)$* between the average throughput time and the number of parcels in a wave (Figure 13). Furthermore, there is a positive correlation *$(r(290) = 0.89, p < 0.01)$* between the average throughput time standard deviation and the number of parcels (Figure 12). There is also a positive correlation *$(r(290) = 0.38, p < 0.01)$* between the number of parcels and the coefficient of variation (Figure 14). Logically, it can be explained that an increase in volume results in an increase in the average throughput time. As more parcels need to be handled the waiting time of several processes will increase (e.g., the time between batch release and picking can increase, the time till the parcel is loaded on the sortation system can increase, etc.). Although, if parcel volumes increase, also more workers will be scheduled to process the volume. As the average throughput time increases, so does the standard deviation. The coefficient of variation in single and double shift (Appendix 1) also increases when the number of orders increases. This means that the relative uncertainty of the average throughput time increases when volume increases. While the coefficient of variation was expected to decrease with higher workloads.

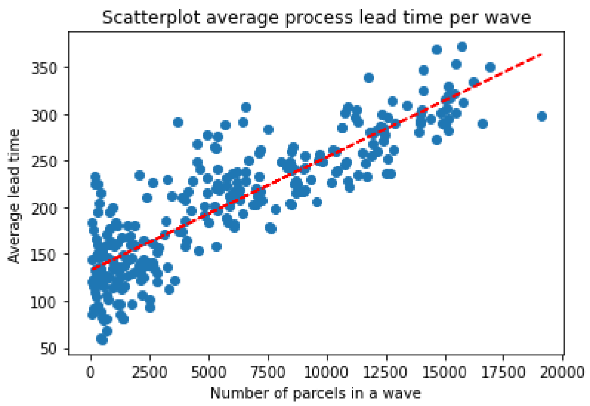

Figure 13: Average throughput time and number of parcels

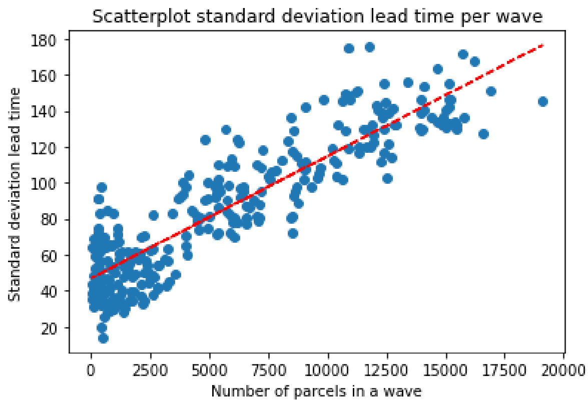

Figure 12: Standard deviation average throughput time and number of parcels

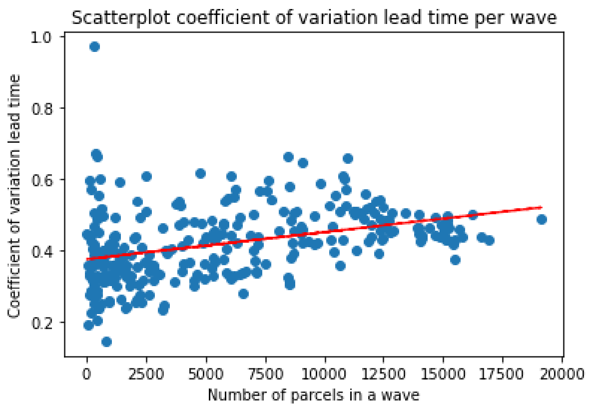

Figure 14: Coëfficiënt of varation average throughput time and number of parcels

3.4. Sortation lanes

3.4.1. Sortation lane differences and associated costs

Sortation lane differences

Parcels sorted to an external lane are directly loaded into the trailer by a worker. Compared to a parcel sorted in an external lane, there are some additional steps to be executed with a parcel sorted to an internal lane, namely:

- Grab order, scan order and place in the roll container car
  - The plan norm for processing on the internal lane is 100 parcels per hour
- Move roll container to the dock
  - No plan norm is available, discussions with managers and some observations result in an duration of 180 seconds and 25 standard parcels can be loaded in a roll container
- Place order from roll container on loading belt
  - No plan norm is available, discussions with managers and some observations result in an duration of 5 seconds per standard parcel.

Both orders sorted to an internal or external lane should be loaded in a trailer, following the following process and norm:

- Grab order and place in trailer
  - The plan norm for processing parcels is 150 parcels per work hour and 350 parcels per work hour for 2 workers

This results in a total time needed per parcel on the internal lane of approximately 68.8 seconds. For a parcel on the external lane approximately 20.6 seconds is needed. This results in 48.2 seconds additional handling time for a parcel and 13.34 minutes for per m^3 sorted via an internal lane. The additional handling costs per m^3 are determined by multiplying the time per m^3 with the cost per work hour. The report only reports the additional minutes due to confidentiality. Because no detailed time study in the handling time of parcels is executed or available, the costs can differ. Therefore, also a second scenario, with higher norms and lower process times is computed (Appendix 5), resulting in 31.8 seconds additional handling time per parcel. The process times and norms are based on discussions with the operations manager and the supply chain manager. The result of both scenarios is face validated with a business analyst.

The cost estimation is based on norms and estimated times. However, the arrival of orders to lanes is not constant and the demand of carriers differ, resulting in different and fluctuating arrivals at the sortation lane. Therefore, workers will not always behave according to the norms and estimated process times. Furthermore, the costs depend on the number of parcels processed. Depending of the number of parcels, a fixed number of workers is always needed to execute the operation (set-up costs). If the number of parcels increases it is easier to achieve more efficiency and the costs per parcel will probably decrease.

3.4.2. Lane and sortation system capacity

To verify whether the norm of parcels processed on the external lane can be reached by the sortation system and the workers, data of the sortation system of one busy day in 2022 is analyzed. The carrier with the highest number of parcels is selected and the processed parcels per hour are counted. As can be seen in figure 15, more than 350 parcels are processed only, between 20:00 and 21:00. Furthermore, the number of parcels processed within half an hour is often above 150 which makes the maximum capacity reasonable. The maximum capacity also depends on the weight and volume of a parcel. Heavier and bigger parcels are more difficult to handle by the workers. Therefore, the norm is based on the average order volume. This results in a maximum sortation lane capacity of 0.36 m^3 per minute. Next to the capacity of a sortation lane, the sortation system in total has a maximum capacity. This capacity is based on the computations of the constructor of the sortation system. The maximum capacity in the MKI outbound warehouse is 4000 parcels per hour, which is 240 m^3 per hour. The maximum capacity in the JTS2 outbound warehouse is 6300 parcels per hour, which is 378 m^3 per hour.

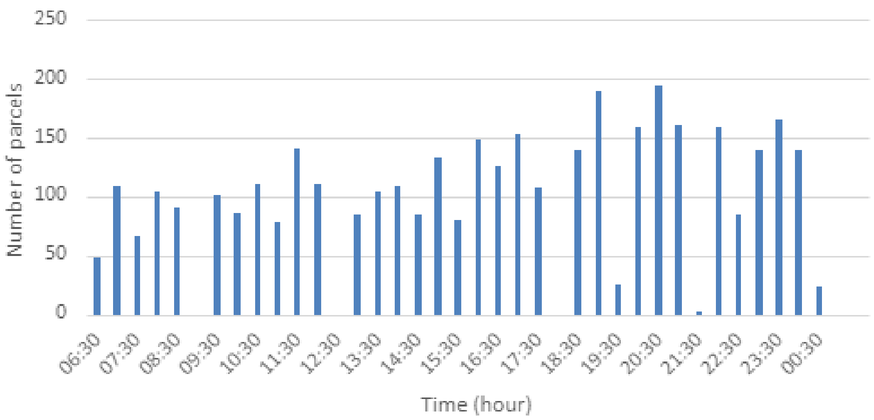

Figure 15: Parcels per half an hour at a single external sortation lane during a busy (40000 parcels) double shift day

3.4.3. Sortation lane change

An order is planned in a wave, however as illustrated in figures 9, 10, and 11, the arrival of waves overlap, and it is not certain when all parcels of a wave are sorted. After the decision is made to change the sortation operation to the next wave, the changes of the sortation lane are executed. If an order is not sorted in its planned wave, it will not automatically mean the due date of this order is not achieved. The possible consequences are listed below:

- The carrier is allocated to the same external lane as the previous wave
  - No additional sortation costs, as the parcel still can be sorted to the external lane.
  - If the parcels are sorted before the planned carrier departure time they can still be loaded into the planned truck.
  - If the planned truck is already departed or fully loaded (a later planned parcel can also go with an earlier planned truck) the parcel can be loaded in the next truck of the carrier (and the service level (release date + 1 day) can still be achieved).
- The carrier is in the next wave allocated to an internal lane instead of an external lane
  - Additional sortation costs are computed, as the handling cost of the internal lane is higher than the external lane.
  - If the parcel is sorted before the planned carrier departure time it can still be loaded into the planned truck.
  - If the planned truck is already departed or fully loaded, the parcel can be loaded in the next truck of the carrier (and the service level can still be achieved).
  - If no other carrier vehicle will depart the same day the parcel will still be sorted and loaded, however, it is not likely the service level (release day + 1) will be achieved.

A sortation lane change causes additional complexity for the workers and operations managers in several aspects. Firstly, the decision should be made when the allocation of the carrier to the lane should be changed. Secondly, the allocation should be changed in the information system of the sortation system. Thirdly, on the work floor, the signs indicating the staging area of the carrier should be changed manually. The staging area is used to deliver non-conveyable parcels and parcels sorted at the internal sortation lane. Fourthly, it should be checked whether all parcels of the previous carrier are put in the departing truck or moved to the new staging area of the moving carrier.

3.4.4. Current sortation lane performance

Figures 16 and 17 show the percentage of orders using the internal and external sortation lanes in a single and double shift period. In a single shift period, the percentage of parcels using the external lane is 82%, compared to 76% in a double shift period. A possible explanation is that during a double shift period more carriers are used to deliver orders to the consumer and the number of parcels processed in a double shift period is on average 35% higher than in a single shift. A Pearson correlation test is executed to see if there is a correlation between the total number of parcels and the percentage of parcels handled at the internal sortation lane (Appendix 2). In a single and double shift period, there is no correlation, in both periods there is a low correlation.

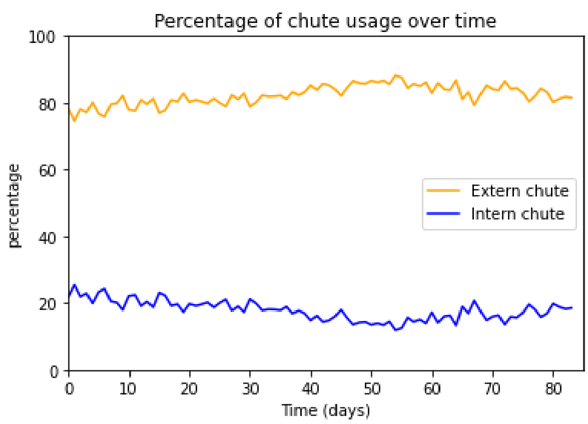

Figure 17: Percentage of orders using internal or external lane during single shift

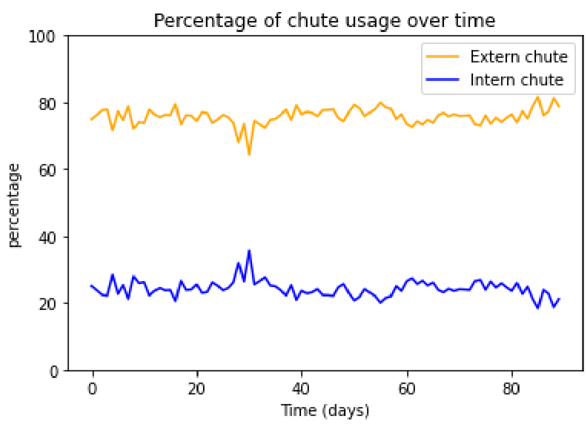

Figure 16: Percentage of orders using internal or external lane during double shift

Figures 18 and 19 show a boxplot of the average number of parcels in a day per sortation lane. On average each internal sortation lane receives 205 parcels per day during a single shift and 349 during a double shift. Each external sortation lane receives on average 855 parcels during a single shift and 1049 during a double shift (Appendix 2).

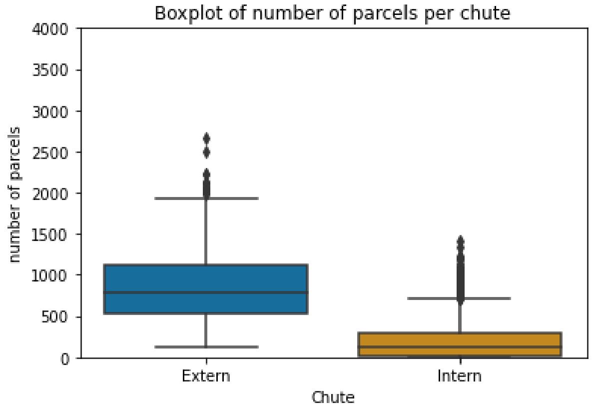

Figure 19: Boxplot of number of parcels per sorting lane (chute) during single shift

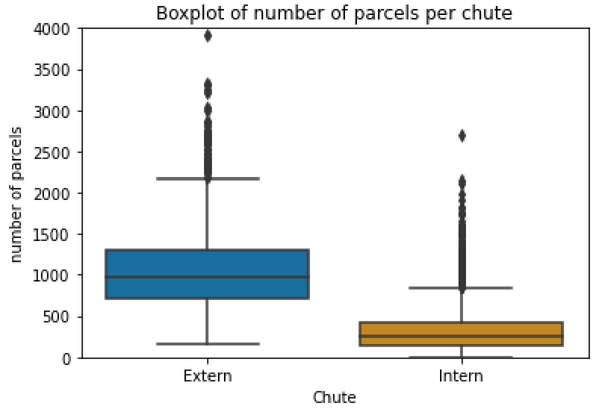

Figure 18: Boxplot of number of parcels per sorting lane (chute) during double shift

In both situations, both lane types have a high standard deviation, and overlap is visible between the number of parcels on the internal and external lanes. However, because the boxplot is based on a longer time period it cannot be concluded that, in some cases, the number of parcels on an internal lane is higher than the number of parcels on an external. However, when the boxplot is made per day (Appendix 2), it can be concluded almost every day there is an overlap between the internal and external sortation area. If an internal lane usage is higher than an external lane it would be more beneficial to switch the carrier assigned to the internal lane to the external lane.

When looking at the daily level, Table 2 shows the average number of lanes on which the number of parcels processed on an internal lane is higher than the number of parcels processed at an external lane. Starting point in the current situation is that nearly carrier-to-lane changes are allowed between waves. Based on this analysis, on average two to three carriers can be better switched daily from an internal to an external lane. This would result in three to five percent additional parcels processed via the external lane. Although it should be kept in mind that not all order information is known upfront, so possibly not all changes can be detected upfront. If carrier changes between waves are allowed during the day, the number of parcels processed at the external lane can be probably higher. Namely, in every wave, another carrier can be processed at an external lane, resulting in more carriers that can be allocated to an external lane during a day.

Table 2: Possible daily lane changes from internal to external lane when daily reviewing lane allocation

Single shift	*Number of times the internal lane is higher than external lane per day*	*Percentage of internal lanes higher than external lanes*	*Possible additional parcels processed on external lane*	*Percentage of all Parcels*
Mean	2.62	13.78%	655	3.32%
Std	0.94	4.95%	332	1.94%
Double shift				
Mean	3.03	15.96%	1336	4.83%
Std	0.77	4.06%	440	1.61%

3.5. Number of parcels per carrier

Figure 20 shows a boxplot of the number of parcels per carrier per day in a single shift period, the figures for all periods can be found in Appendix 3. The figures show that carriers are fluctuating in the number of parcels per day, furthermore, some carriers have a higher variation than others. All this makes a fixed lane allocation for some carriers for a long planning horizon doubtful.

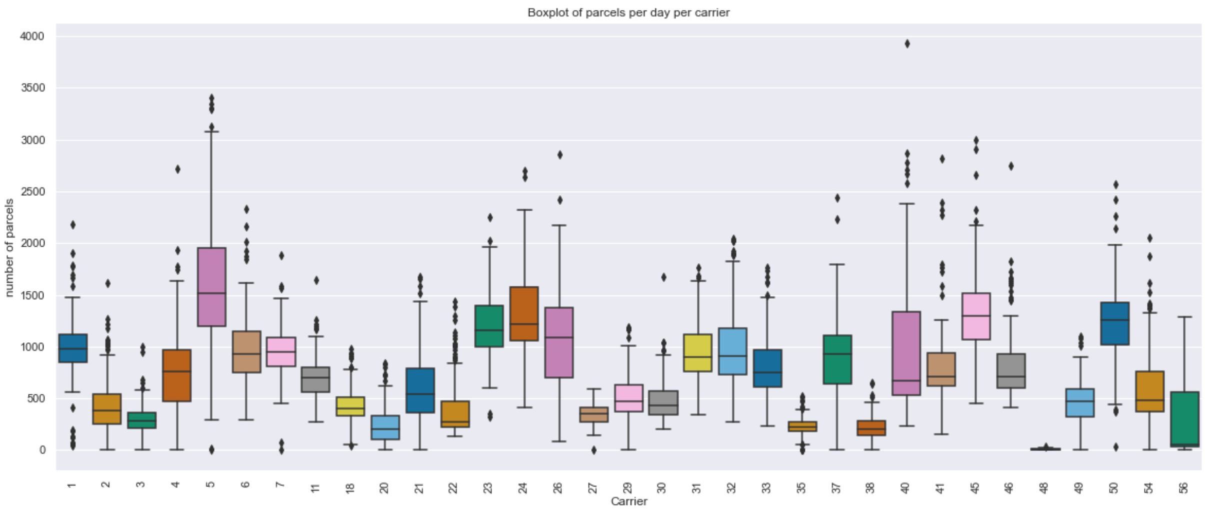

Figure 20: Boxplot of number of parcels per carrier per day (only contains carriers with a yearly volume higher than 35000)

3.6. Order information

Most of the information on the orders picked in a day is available before the waves are released. On average 77% of the order information in a single shift period is already known before the day starts (71% in a double shift period). This indicates that before the waves are planned and released it could already approximately be determined how many parcels each sortation lane will receive. Thereby making changes to the carrier-to-lane allocation possible before the sortation starts.

Therefore, the planning horizon for which the carrier-to-lane allocation is made can be important. When updating (planning) the carrier-to-lane allocation daily, the already available order information can be used. While when updating the carrier-to-lane allocation on a planning horizon longer than a day, the information to determine the allocation can only be based on historic data. However, a shorter timeframe (e.g., a week instead of a month) can include more recent trends.

3.7. Main challenges in the sortation area

Currently, the allocation of carriers to different sortation lanes is fixed for a long planning horizon (e.g., several months) and only weekly some changes are executed. When a carrier on the internal lane is assigned a higher number of parcels, than a carrier that is planned on the external lane, it will not be changed. This results in a handling time increase in two ways: the packages in the internal area should be handled by a worker, and the worker planned on the external lane handles fewer parcels than possible. Furthermore, parcels sorted at an internal lane require more handling steps. Determining the carrier-to-lane allocation on a shorter planning horizon (e.g., day instead of month) can probably help to sort more parcels on the external sortation lane, however, the maximum effect is limited as can be seen in Table 2. Therefore, to process more parcels on the external sortation lane it is also needed to schedule more sortation lane changes during the day. The current fixed planning only includes a few sortation lane changes between the waves during the day. A sortation lane change, during the day, can be helpful to allocate more carriers to an external lane and so increase the external lane utilization. However, because of the overlapping waves (figures 9 and 10) and therefore overlapping parcel arrival of different carriers (figure 11), it is difficult to determine the moment of change. Furthermore, the throughput time of orders in the warehouse depends on several points: product category, additional processing tasks (packaging, memory lane), warehouse, and possible disruptions. The throughput time of an order and the overlap of the waves make it hard to decide when to change a carrier from a lane.

From the analysis above, it can be concluded that creating a more dynamical carrier-to-lane allocation can result in a potential process improvement. First, it should be possible to plan lane changes between carriers in-between waves, considering the order warehouse throughput time and wave overlap. Secondly, the benefits of the solution with shorter (e.g., day) or longer planning horizons (e.g., month) should be determined. Chapter 4, the conceptual design, will focus on the requirements for a solution design of a dynamic allocation. Chapter 5 will in detail discuss the proposed solution design.

4. Conceptual design

In this section, the general outline and modelling decisions for the carrier to wave and lane allocation model are addressed.

4.1. Design objective and requirements

The purpose of the model is to optimally allocate carriers to a sortation lane, so that the usage of the internal sortation is minimized and in that way, the external sortation is maximized. This is under the condition that all orders and carriers are handled within their promised timeframe. Minimizing the use of the internal sortation lane should result in a minimization of the handling cost in the sortation area.

First of all, to handle more parcels on the external sortation lane, the allocation should allow planning multiple carries on one lane during the day. In other words, allow changes between the waves. When allowing changes, the maximum possible number of carriers on an external lane during a day is equal to the number of waves times the number of external lanes. While if only one carrier is allowed on an external lane during the entire working day, this number is equal to the number of external lanes.

Secondly, the model should prevent unnecessary complexity in floor operations. Therefore, the model should ensure that no carrier changes between external lanes are planned. A change from an external lane to another external lane is of no benefit because all external lanes are equal. Furthermore, when a carrier is often served at the same lane it helps the workers to learn the topography of the sortation area.

Thirdly, the model should handle the stochastic order throughput time and overlapping waves such that orders are delivered within the required time to the customers. Therefore, decisions should be made on the wave capacity, the number of waves and wave duration.

The performance of the model is measured in several performance measures, namely the percentages of the volume of parcels handled through the external lanes and internal lanes and the total additional handling costs for the internal sortation lane. Lastly, the service level, the percentage of parcels sorted within 24 hours, should be considered. To achieve the service level, all available orders should be scheduled if system capacity allows and orders should preferably be scheduled as early as possible.

4.2. Model decisions

The allocation decision consists of two steps. Firstly, to allocate the carrier to a wave and lane and secondly to allocate the order to the wave (wave batch creation). Allocating the carrier to a wave and lane is a decision that can be made for a longer time horizon based on a forecast. While allocating orders to a wave happens daily based on the carrier-to-lane allocation. An order can namely only be allocated to a wave when the order has been received, therefore it is only possible to determine this at a daily level. Furthermore, the carrier-to-lane allocation has the highest impact on the objective “minimizing the usage of the internal sortation lanes”, as the order to wave allocation only follows the carrier-to-lane and wave allocation outcome. Therefore, the order to wave allocation can be seen as an operational (lower level) decision, while the carrier-to-lane and wave allocation can be seen as a more tactical (higher level) decision (figure 21).

Although the process of picking and sorting orders is a stochastic process, the choice is made to use a mixed integer programming (MIP) model for the carrier to wave to lane allocation and the order to wave allocation. Because MIP is a powerful method to solve the problem given the size and complexity of the problem. Using a deterministic approach is possible by setting the system boundaries (capacities) in the MIP in such a way that the required performance can still be achieved. In addition, a discrete modelling approach is preferred because many events are discrete, which make the operation not too complex (e.g. wave batch release time, time to change carriers between lanes).

The system boundaries should be determined such that most parcels are sorted within the timeframe of the wave and therefore are sorted to the allocated sortation lane. To compute the system boundaries of the allocation model a procedure (heuristic) is needed. The procedure computes the maximum wave volume, wave release time and the switch between the waves (sortation change time), based on the stochastic order warehouse throughput time and the expectation of orders sorted within the wave as allocated by the dynamic allocation model.

To verify the performance of the dynamic allocation model in the actual system, a simulation model is needed. The simulation model is used to verify how the system boundaries settings perform in the actual situation since an order sorted outside a wave does not necessarily affect performance (section 3.4.3.). Also, the simulation model is used to measure the performance of the actual system on different time horizons.

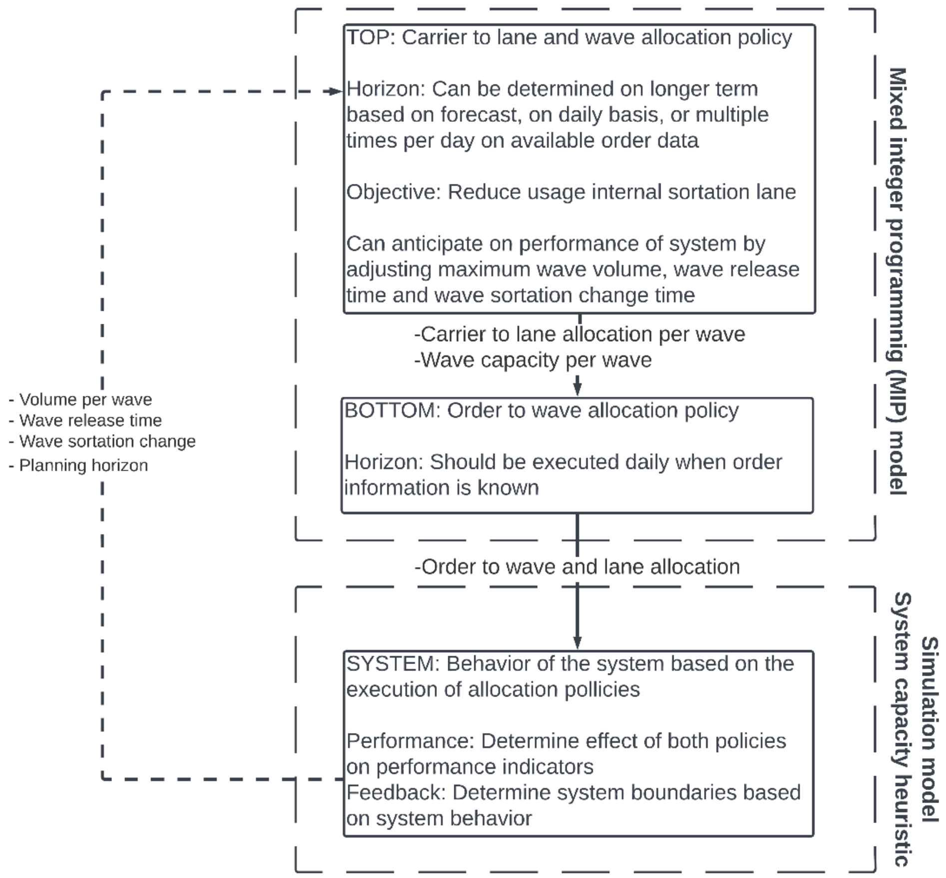

Figure 21: Model approach and hierarchy

4.3. Workday layout

The number of work hours is fixed, 8 hours during a single shift and 16 hours in a double shift (figure 8). During a single shift, only a two-wave scenario is possible, as the average historic order throughput time for a wave for non-bundling orders is already 4 hours and 10 minutes. This makes it not reasonable to plan more than two waves. A one-wave scenario is not possible, as the wave would then end at the end of the working day, which means not all the parcels are sorted on time for carriers with only early truck departure slots. During a double shift, it is possible to batch orders in two, three or four waves.

4.4. The allocation model design (MIP)

The allocation model should make two decisions. First, which carrier is allocated to which lane in which wave. The second decision is to which wave the order is allocated. The overall purpose is to minimize the use of the internal sortation lane, this is modelled by minimizing the additional cost of using the internal sortation lane.

The additional handling costs are modelled per volume (m^3), as every order has another volume and the volume influences the handling of a parcel. A worker can handle more smaller parcels than heavier parcels at the (internal) sortation lane and the same applies for loading orders into the truck at the dock. Furthermore, at an internal sortation lane a bigger parcel requires more storage space in the container in which it is transported to the dock. Consequently, bigger parcels require more transport movements between the internal lane and the dock. Furthermore, the departing trucks have a capacity in volume. Therefore, in line with this, the system capacities (e.g., lane capacity, wave capacity) are also modelled in volume (m^3) rather than a number of parcels. However, with small adjustments to the model, the model can also deal with number of parcels instead of volume (m^3).

4.4.1. The carrier-to-lane allocation

The decision on which carrier to allocate to which lane and in which wave is based on the order due date, the lane capacity, and the total wave capacity. The order due date is determined based on the carrier departure time as specified in the transport planning. Orders that were available first are assigned to the first departing truck of their carrier (FIFO).

The carrier-to-lane allocation should be determined before the day starts. Depending on the time horizon, the carrier-to-lane allocation can be determined on a forecast based on historic data or on current order data.

The data analysis shows that most orders are known before the working day starts. For a one-day time horizon, the remaining order flow should be forecasted (figure 22). The forecast is determined by dividing the remaining orders equally over the time between the start of the workday and the start of the last wave, equally over the carriers based on the carrier fraction of that day. When the carrier-to-lane allocation is determined over a longer time horizon (e.g., week, month, etc.), the order information per carrier is based on the forecast of vidaXL of that period.

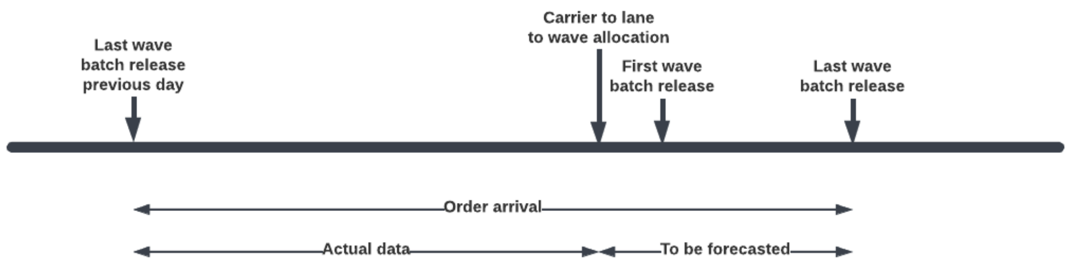

Figure 22: Order information before carrier-to-lane to wave allocation (daily horizon)

4.4.2. The order to wave allocation (wave batch creation)

If a one-day time horizon is used, the order to wave allocation is executed simultaneously with the carrier-to-lane allocation. Only orders that arrive after the release of the first wave (the forecasted orders), should be assigned to a lane in the waves that follow according to the defined carrier-to-lane allocation. If the time horizon is greater than one day, the model should be used to assign the orders with the carrier-to-lane allocation as a fixed input.

A separation is made between standard orders and packing orders. Packing orders must visit the packing process, standard orders are the orders that follow all other processes. The separation is made because the average order throughput time of a pack orders is approximately 1.5 times as high as a standard order. The higher throughput time, results in a significant part of the packed orders not being sorted within the allocated wave, as the wave duration is based on a standard parcel. Furthermore, on average only two to three percent of the orders require packing. Therefore, packing orders are not allocated by the MIP to a wave. To ensure packing orders are handled in time, the packing orders are allocated to the first possible wave. The wave system capacity is lowered by a fixed capacity for packing orders to ensure the system capacity is not exceeded.

4.4.3. Model assumptions and constraints

Several assumptions and constraints are made to define the scope of the model. These assumptions are listed below.

Assumptions

- The order departure time (due date) is based on the carrier departure time. Based on the arrival time of the order the orders are assigned FIFO to a carrier, from which the carrier departure time will follow.
- The truck departure time (and so the order departure time (due date)) is fixed, a truck departure will not be delayed.
- Sufficient carrier departure dates are always available for the available orders.
- From the moment an order is arrived, it can be planned in a wave, regardless of the order (carrier) departure time. An earliest order release time is not needed, as carrier trucks have no arrival time. Trailers to load the planned order are always available, because vidaXL uses its owns trailers that are identical and can visit every location. Furthermore, enough empty trailers are always available.
- A wave has a fixed wave batch release time and a fixed wave sortation change time. The wave batch release time and end change time are based on the system capacity heuristic.
- A wave has a maximum wave capacity (in m^3) and duration. The wave duration is based on the system capacity heuristic. The maximum wave capacity is based on the maximum sortation system capacity per hour and the wave duration.
- Packing orders are not allocated by the MIP to a wave. To ensure packing orders are handled in time, the packing orders are allocated to the first possible wave and the wave system capacity is lowered by a fixed capacity for packing orders to ensure the system capacity is not exceeded.

Constraints

- Each carrier should be assigned to one sortation lane per wave, this can be an internal or external sortation lane. Also, when no orders are allocated to the carrier in a wave, the carrier should have a lane to handle parcels that are delayed from previous waves.
- A sortation lane, internal or external, can only handle one carrier per wave.
- The volume processed on a lane, cannot be higher than the lane capacity. The sortation capacity of a lane depends on the duration of the wave. It is determined by multiplying the capacity per hour with the wave duration.
- The volume processed during a wave cannot be higher than the maximum wave capacity.
- All orders should be allocated before the assigned order (carrier) departure time (due date).
- An order is only allowed in a wave if the order is available in the system before the wave batch release and has a departure time (due date) after the sortation end of a wave.

4.5. System design (System boundaries & simulation model)

4.5.1. Design purpose & decisions

Purpose

Since the warehouse order throughput time is stochastic, a method is needed to determine the system boundaries for the deterministic model and to determine the actual performance of the model. The stochastic order throughput time induces that orders are not always sorted within their allocated wave, which can cause orders sorted on another lane than planned (e.g., internal instead of external) which lowers the performance. A system capacity procedure (heuristic) is developed to determine wave capacity, wave release time and wave change time, such that a minimum percentage of orders allocated by the dynamic allocation model are sorted into the allocated wave.

The simulation model is needed to determine and verify the actual performance of the dynamic allocation model and the system boundaries as discussed in section 4.2. Namely, if an order is not sorted in a wave, it does not necessarily affect performance (see section 3.4.3). If, for example, an order does arrive in the second wave, the carrier of that order can still be planned on the external lane. Furthermore, the performance of the allocation model in the system does not only depend on the stochastic order throughput time, but is also influenced by the maximum queue capacity of an external lane, the processing capacity of an external lane and lane availability due to truck changes. To determine the effect of orders not sorted to the desired wave on the performance of the model the simulation model is needed. The concept of the simulation model is discussed in this section.

Design decision

The order throughput time is modelled as a stochastic process for both standard and packing orders to determine the arrival of the order at the sortation system. The arrival time is the most important factor whether an order is sorted internally or externally. Next to this, some orders can be sent to a backup (internal) lane if the sortation lane is not available due to a full external lane queue or due to a truck change. Since the outcome of the simulation model is interested in the number of parcels that cannot be sorted on the external lane, only the process of the external lane should be modelled, in terms of queue and process rate. This is because parcels that cannot be processed on the external lane, will always be processed on an internal lane, regardless of the number of arrivals.

It is assumed that the external sortation lane queue length is deterministic and based on the number of standard parcels (size, length). This deterministic length is determined based on a discussion with the operations manager. In real-time, the queue length can differ, as the length of a parcel and the length of the telescopic conveyor can differ. Also, the process rate of orders at the external lane is assumed to be deterministic based on the number of standard parcels (size, length) that two workers can handle during an hour. Workers are not modelled in the allocation and the simulation model. However, the maximum processing rate depends on the number of workers. One worker is always required. Other workers can switch continuously to busy lanes. It is assumed enough workers are available to switch between the sortation lanes and deal with the maximum workload if needed. Furthermore, the time needed for a truck change is also modeled deterministic. The decision to model queue length and process rate as a deterministic process is made because it only has limited influence on the number of parcels processed on the external lane. It is expected that the model still gives an accurate indication of parcels moving to the internal lane when the arrival rate of parcels at the external lane is too high.

4.5.2. Simulation Process

The simulation models the process as visualized in figure 23. Orders arrive and wait in a queue till they are released. According to the order to wave allocation of the MIP, the orders wave batch is created. Orders are processed via the standard order picking process or if the order requires packing via the packing order picking process. Both processes are modeled with a different stochastic order throughput time. If the order is picked (and packed), the order will go to the internal or external sortation lane based on the carrier-to-lane to wave allocation. If the order goes to the external lane, it needs first to be checked whether the lane is available. If the queue of the external lane is full, the external lane is not available. If the lane is not available, the order will proceed to the carrier backup lane (an internal lane) where the order is sorted and afterwards loaded in a truck. When the order is in the external lane queue it is processed FIFO at a fixed deterministic rate per minute. Only when the truck is full, no orders are processed for a fixed deterministic time to facilitate the truck change. During the truck change orders remain in the queue and new orders can enter the queue until the maximum is reached.

4.5.3. System assumptions

In this section, the system assumptions made to develop the simulation model are listed.

- The stochastic throughput time is divided in two process: packing orders and standard orders.
- At an external lane parcels are processed according a deterministic process rate.
- An external lane has a deterministic queue length.
- At an internal lane all parcels that arrive are directly processed, no queue exists.
- Always enough workers are available to process parcels at the maximum process rate of the external sortation lane.
- The truck departure time is fixed and is the same on which the order due date is determined in the MIP.
- Loading of a planned truck can start at any time
- The capacity of a truck trailer is fixed
- All orders that are allocated to a wave can always be released and picked from the warehouse

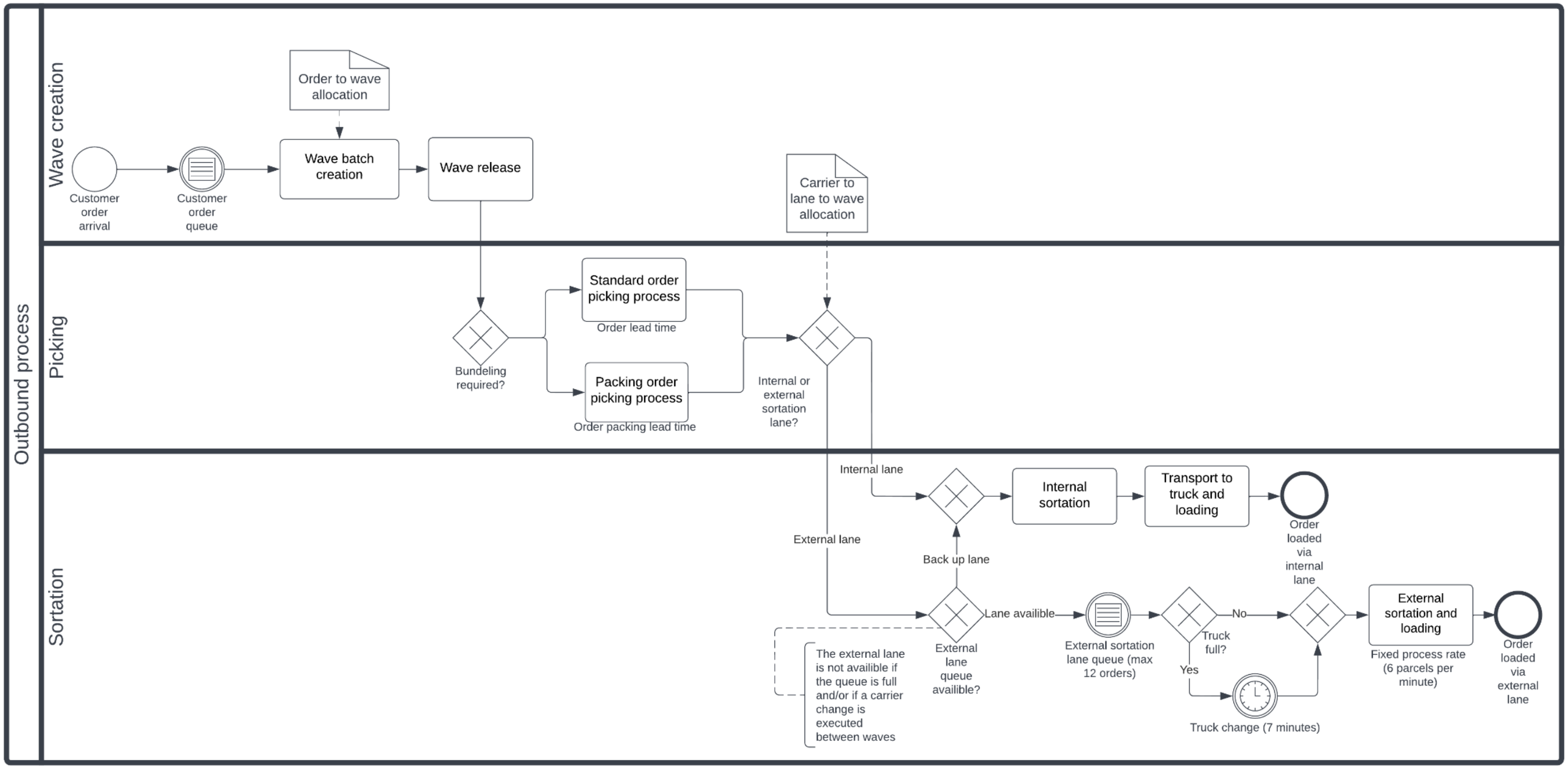

Figure 23: BPMN diagram, outbound process simulation

5. Detailed design

In this chapter the mathematical model, system boundaries heuristic and simulation model are presented.

5.1. Mathematical model

A mixed integer quadratic program (MIQP) is developed for the order to wave allocation and the carrier-to-lane allocation. A MIP approach is chosen as it results in a better solution than the use of heuristics or simple priority rules and the computation time is acceptable. Furthermore, no assumptions have to be made that simplify the situation such the model practically unusable anymore.

5.1.1. Parameters

W consists of the number of waves in which the orders are divided. A working day has several waves (w) each handling a batch of orders. Each wave has a release time, a start sortation time and end sortation time. At the start time of the wave (wave release time) the batch is released to the warehouse at once.

$W = \{1, \dots w\}$ Set of waves

Set C consists of all the carriers that will ship orders.

$C = \{1, \dots c\}$ Set of carriers

Set L consists of the number of lanes available for sortation.

$L = \{1, \dots l\}$ Set of lanes

Set O consists of the all the orders that should be planned during the day.

$O = \{1, \dots o\}$ Set of orders

A_l is a parameter indicating if lane l is an external sortation lane (value 1) or an internal sortation lane (value 0).

$$A_l \quad \begin{cases} 1, & \text{external lane} \\ 0, & internal\ lane \end{cases}$$

$B_{c,o}$ indicates which carrier c handles order c. If an order is handled by a carrier the value of $B_{c,o}$ will be 1.

$$B_{c,o} \quad \begin{cases} 1, \text{if order o is handeld by carrier c} \\ \qquad 0, otherwise \end{cases}$$

$D_{w,o}$ indicates whether an order is allowed in a wave based on the order arrival time (the moment the order is available in the system), the order due date (departure time), wave release time and wave end sortation time. The order due date is determined based on the carrier departure time and the truck capacity. Each carrier has one or more truck departures during a day. A truck departs at a fixed time and has a fixed capacity in m^3. A carrier with more truck departures may have different departure times during a day. Orders are assigned FIFO to a truck departure time until the maximum capacity of the truck is reached or the arrival time of the order is later than the latest wave release possible for the truck. The process will continue with all truck departure times, until all orders are assigned to a truck departure time. An order is allowed in a wave when it has arrived in the system before the wave release and when the due date of the order is later than the end sortation time of the wave.

$D_{w,o}$ $\begin{cases} 1, \text{if an order is allowed in a wave w} \\ 0, otherwise \end{cases}$

$PC_{c,l}$ indicates the preference to allocate a carrier to a lane, the range is between 0 and 1. With 0 indicating a high preference and 1 indicating a low preference. The preference for an external lane differs between the carriers, while the preference for an internal lane is always 1 for every carrier. Giving a carrier a preference for an specific external lane ensures that a carrier is often planned on the same lane. This prevents that the carriers, that are planned on the external lane are divided randomly every wave, which prevents unnecessary changes between the waves for carries at the external lanes.

$PC_{c,l} = Preference\ to\ allocate\ a\ carrier\ c\ to\ a\ lane\ l$

$PW_{w,o}$ indicates the preference to allocate an order to a wave, the range is between 0 and 1. With 0 indicating a high preference and 1 indicating a low preference. Ideally, orders are planned as early as possible, it gives an order more time and reduces the risk of the order from missing the truck departure if there is a delay. Therefore, the preference is the highest during the first possible wave and decreases during the following possible waves.

$PW_{w,o} = Preference\ to\ allocate\ an\ order\ o\ to\ a\ wave\ w$

Every order has a volume V_o which is measured in m^3 .

$V_o = Volume\ of\ order\ o\ in\ m^3$

The use of the internal sortation lane has additional costs compared to the external sortation lane per m^3.

$C^I = additional\ costs\ for\ the\ use\ of\ internal\ sortation\ lane\ per\ m^3$

Each lane has a maximum volume that can be processed. This depends on the duration of the wave. It is determined by multiplying the capacity of an hour and the duration of the wave.

$CAPL_w\ = maximum\ capacity\ of\ lane\ in\ m^3$

Each wave has a maximum volume that can be processed. This depends on the duration of the wave. The maximum wave capacity is determined by the simulation model.

$CAPW_w\ = maximum\ capacity\ of\ a\ wave\ in\ m^3$

5.2.2. Decision variables

Decision variable $X_{w,c,l}$ represents the decision to assign a lane to a carrier in a wave. If the carrier is assigned to a lane in a wave $X_{w,c,l}$ becomes 1. If not $X_{w,c,l}$ becomes 0.

$X_{w,c,l}$ $\begin{cases} 1, \text{if lane l is assigned to carrier c in wave w} \\ 0, otherwise \end{cases}$

Decision variable $Y_{w,o}$ represents the decision to assign an order to a wave. If an order is assigned to a wave, it becomes 1. If not $Y_{w,o}$ becomes 0.

$Y_{w,o}$ $\begin{cases} 1, \text{if order o is assigned to wave w} \\ 0, otherwise \end{cases}$

5.2.3. Objective function

The objective (1) minimizes the additional cost for using the internal sortation lane (first part). Furthermore, it maximizes the preference for the allocation of a carrier to a sortation lane (second part) and the allocation of an order to a wave (third part). Although the function aims to minimize costs, the preference is maximized, because the parameters $PC_{c,l}$ and $PW_{w,o}$ indicate a high preference with a low value and a low preference with a high value.

$$\min \sum_{w \in W} \sum_{c \in C} \sum_{l \in L} \sum_{o \in O} C^I (1 - A_l) X_{w,c,l} V_o B_{c,o} Y_{w,o} + \sum_{w \in W} \sum_{c \in C} \sum_{l \in L} PC_{c,l} X_{w,c,l} + \sum_{w \in W} \sum_{o \in O} PW_{w,o} Y_{w,o} \quad (1)$$

The objective (1) can be rewritten in (2):

$$\min \sum_{w \in W} \sum_{c \in C} \sum_{l \in L} \sum_{o \in O} X_{w,c,l} \left(PC_{c,l} + C^I (1 - A_l) V_o B_{c,o} Y_{w,o} \right) + PW_{w,o} Y_{w,o} \quad (2)$$

5.2.4. Constraints

Each carrier should be assigned to one sortation lane per wave

$$\sum_{l \in L} X_{w,c,l} = 1 \qquad \forall\, w \in W, c \in C \quad (3)$$

Each sortation lane can only handle one carrier per wave

$$\sum_{c \in C} X_{w,c,l} \leq 1 \qquad \forall\, w \in W, l \in L \quad (4)$$

The volume processed on a lane cannot be higher than the lane capacity during a wave

$$\sum_{o \in O} V_o B_{c,o} Y_{w,o} \leq CAPL_w \qquad \forall\, w \in W, c \in C \quad (5)$$

The volume processed during a wave cannot be higher than the maximum wave capacity of the wave

$$\sum_{c \in C} \sum_{o \in O} V_o B_{c,o} Y_{w,o} \leq CAPW_w \qquad \forall\, w \in W \quad (6)$$

All orders should be assigned before the defined due date

$$\sum_{w \in W} D_{w,o} Y_{w,o} = 1 \qquad \forall\, o \in O \quad (7)$$

The following constraints ensure that the decision variable, $X_{w,c,l}$, $Y_{w,o}$ are binary and can only take values 0 and 1.

$$X_{w,c,l} \in \{0,1\} \quad (8)$$

$$Y_{w,o} \in \{0,1\} \quad (9)$$

The MIQP model will become infeasible when the total volume of orders that can only be processed in one specific wave is higher than the capacity of a wave or when the total volume of orders of a carrier that can only be processed in a specific wave is higher than the lane capacity of a wave. Also, when the total volume of orders for a carrier is higher than the sum of the lane capacity in all waves. If so a carrier can be split in two or more carriers which will increase the total lane capacity for the specific carrier.

5.2. System capacity

To determine the system boundaries for the MIQP, the duration of an wave and the capacity of a wave should be determined. To do so the time of arrival of orders at the sortation lane should be determined. Therefore, the time between the wave batch release and the arrival at the sortation lane is modeled as the throughput time of an order in the warehouse.

5.2.1. Order throughput time

Orders are divided into two types, namely the standard orders and the orders that require packing. Packing orders are separated because section 3.3 shows that the average order throughput time is 1.5 times higher than the average of all orders. The order throughput time of orders picked in all the different warehouses and orders picked that visit the memory lane are all modeled as the standard order throughput time.

The throughput time of an order is defined as:

Throughput time = Arrival time of order at sortation lane – Wave batch release time of order

The analysis in section 3.3 shows that an increase in the number of orders results in an increase in the mean of the throughput time. Analysis further suggests that the coefficient of variation (cv) increases when the number of orders increases, while the cv was expected to decrease when the number of orders in the system increases. An increasing coefficient of variation would mean that the system is not scalable and would end up in unmanageable process when increasing the number of orders. For that reason MIP would not be the appropriate to model the process. Therefore, an additional analysis is carried out on the data of an single shift period (Appendix 1).

First of all, only the first and second wave are considered, since these are the main waves in a day. Secondly, the first and second wave are analyzed separately. The results show that the coefficient of variation in the first wave decreases when the number of orders increases, while in the second wave a small increase is suggested.

The difference in the two waves can have several causes. First of all, the first wave starts with an empty system, the second wave starts when some orders of the first wave have yet to be picked and sorted. The full system capacity is therefore not directly available at the start of the second wave. Secondly, errors or interruptions in the system, that occur during the day, can accumulate and have therefore a bigger impact on the second wave. Thirdly, the second wave is not always completely finished, because it ends at the end of the workday. Orders that are not completed will be released the next day, therefore the full distribution of all released orders is not known.

Furthermore, an additional analysis is carried out whether enough workers are added to the system when the number of orders increases (Appendix 1). vidaXL has a plan norm of one additional working hour for 80 picks. The mean of the picks per hour is 86.98 with a standard deviation of 11.41. Furthermore, the analysis shows that the number of picks per working hour increases as the number of picks increases, however still the number of picks per hour seems reasonable for a high number of picks in a day.

As a result, it is chosen to use only the data from the first wave to model the throughput time of an order in all waves. Two main remarks to be made. Firstly, it is not taken into account that not all pick capacity is available at the start of the second wave. Secondly, at the start of the day the sortation workers start one hour later than the order pickers, therefore the first hour no orders can be sorted and some orders are buffered at the sortation system. While during the second wave also orders can arrive at the sortation lane during the first hour. Therefore, when using the first wave, the arrival pattern in the first hour of the second wave will be a bit lower and in the second hour a bit higher. Although, it will have some impact on the computation of the system capacity and simulation, this modeling can still deliver a good approximation.

5.2.2. Modeling of order throughput time

To model the throughput time the data of a single shift period of wave 1 are used. Since the performance on a single shift timeframe should also be achievable on a double shift timeframe. Two data corrections are made. First of all, the data is cleaned up, 2 days with different working schedules are deleted. Secondly, the data are corrected for the breaks of the warehouse workers.

Standard orders throughput time

The mean order throughput time of a wave increases when the number of orders that are processed in a wave increases, a Pearson correlation of 0.75 *(r(80) = 0.75, p < 0.0001*). Furthermore, the coefficient of variation decreases when the number of orders in wave increases, a Pearson correlation of -0.42 *(r(80) = -0.42, p < 0.0001)*. To determine the system capacity (determine the time in a wave till X% of the orders are sorted) while these relations are incorporated, two possible approaches can be used. Namely, by computing the expected time based on historical data of the same wave size or by determining a method that can estimate a continuous distribution of the throughput time for each number of orders. A continuous distribution approach is chosen, as only a limited number of data is available. Furthermore, it allows to model larger wave size for growth scenarios that have not occurred in the past.

Several distributions are suitable to model the order throughput time (Baker & Trietsch, 2009; Gudum, 2002; Nielsen et al., 2014). The normal, log-normal, gamma and beta distributions are chosen to be tested. For the computation of the system capacity and the simulation model it does not depend on which distribution is chosen, but it is beneficial if the distribution has the following requirements:

- Finite support, the sortation process is a terminating process and it is therefore not reasonable to allow orders to remain in the system for more than one day. Furthermore, supervisors actively solve problems with orders that stay too long in the system.
- Non negative, the throughput time of an order cannot take a negative value.
- Continuous distribution, an order can arrive at any time during the period of the distribution.
- The distribution should have a good fit

Based on these requirements a shifted beta distribution is chosen to model the throughput time ($\text{Throughput time} \sim Beta(\alpha, \beta, a, c)$). With α and β as shape parameters and a (minimum) and c (maximum) as location parameters. The shape parameters of the beta distribution are fitted with a two moment fit based on the mean (μ_t) and variation (σ_t^2) of the throughput time belonging to the number of orders in a wave (Johnson et al., 1995). a is set to 60, as it takes 60 minutes before the first orders are sorted. c is set to 720 by looking to the fit of the tail of the distribution, by comparing beta distributions based on different number of orders to historical data of waves that have approximately (+/- 500) the same number of orders (Appendix 4). Furthermore, the duration of a working day is taken into account, 540 minutes during a single shift and 1020 minutes during a double shift. The c parameter for a double shift is set to 1200, as waves consist of a larger volume, in line with the single shift 180 minutes more than the total work day.

To determine the mean (μ_t) of the throughput time a linear regression model based on the number of non-packing orders in a wave is developed. The analysis can be found in appendix 4. The intercept of the regression model can partly be explained by the fact that the sortation operation starts 60 minutes later than the picking operation, some time to be loaded on the sortation system and travel time to the sortation lane. However, as the intercept is higher than expected, the line is only used for larger waves (>6000 non-packing orders). Furthermore, the shape of the beta distribution will change when the number of orders is lower than 6000, as α will be smaller than 1.

$\mu_t = 0.008970 \text{ numbe}rofnonpackingorders + 120.69$

To determine the standard deviation (σ_t) a power law is fitted based on regression. The analysis can be found in Appendix 4.

σ_w =2.29975$\mu_w{}^{0.7227}$

With the use of the linear regression and power law μ_t and σ_w can be computed for every number of orders in a wave bigger than 6000. Based on this the beta throughput time distribution can be fitted. To see if the shape of the beta distribution fits well, the beta distribution of several order sizes is compared with historical data of waves that are about the size (+/- 500) of that wave (Appendix 4). Overall, it can be concluded that the fit of the beta distribution is good.

Pack order throughput time

The orders that are bundled by visiting the packing area are only a small part of the process (2-3% of the orders). The mean throughput time of pack orders is approximately 1.5 times higher, therefore pack orders are not taken into account in the MIQP model. Instead the capacity needed is subtracted from the total capacity. Only for the simulation model the throughput time distribution of the pack orders is needed. This to take into account the influence of the orders on the system capacity in terms of lane queues. It is assumed that the mean and standard deviation of the throughput time of pack orders does not depend on the number of orders, as the process can contain only a limited number of orders and limited data is available for extensive data analysis. Therefore, the parameters of the beta distribution are set once by a two moment fit on the mean (μ_{tp}) and variation (σ_{tp}^2), with an μ_{tp} of 333.1489 and an σ_{tp} of 121.3298. The a is set to 60, as it takes 60 minutes before the first orders are sorted. The c parameter is set to 1140 by looking to the fit of the tail of the distribution compared to historic data. This results in the following beta distribution: $\text{Throughput time pack} \sim \text{Beta}(\alpha = 3.5335, \beta = 10.4377, a = 60, c = 1140)$.

A Kolmogorov-Smirnov (KS) test with a 5% significance level is executed to test if the pack orders follow a the specified beta distribution (Lopes, 2011).

H_0 : The pack order throughput time is beta distributed with $\alpha = 3.5335, \beta = 10.4377, a = 60, c = 1140$
H_a: The pack order throughput time is not beta distributed with $\alpha = 3.5335, \beta = 10.4377, a = 60, c = 1140$

The result of the KS test (n=500) gives a KS statistic of -0.06 and a P-value of 0.07, which means that the null hypothesis cannot be rejected, suggesting that the pack order throughput follows a Beta distribution.

5.2.3. Determining system capacity

With the use of the throughput time distribution the system boundaries of the MIQP model can be set. This is done by determining the maximum number of orders that can be processed in a wave and by determining the moment of wave change. Based on the maximum number of orders in a wave the $CAPW_w$ is determined by multiplying with the mean volume of an order. The moment of wave change is needed to determine whether an order can still be handled in the wave $D_{w,o}$. If the carrier departure time is later than the wave change, the order will be allowed in the wave.

To determine both the moment of change and the maximum capacity, an alliterative procedure (heuristic) is developed which is visualized in figure 25. As input the fraction of the number of total orders handled in a wave is needed. The fraction of number of orders in a wave depends on when the first wave needs to be finished, the larger a wave, the longer it will take to completely finish it. When a wave needs to be finished often depends on when a carrier truck needs to leave. Furthermore, the maximum fraction of orders not sorted in the required wave should be set beforehand. This value indicates the percentage of orders that are potentially sorted to another sortation lane, because the carrier-to-lane allocation is changed between the waves. Also, the minimum fraction of orders of wave sorted at the end of wave 2 should be indicated. Handling the full tail of the distribution does not create an efficient work environment, therefore a part of the orders that are not handled are released the next work day. However, the orders of wave 2 that are not handled have an influence on the customer service level, and therefore the decision should not only take into account the efficiency of the operation. Moreover, currently the tail of the distribution is often solved by working overtime with a part of the sortation workers. Finally the duration of a working day affects the capacity. With the use of the continuous throughput distributions that can be defined for every μ_t and σ_t^2 and the heuristic defined below, ultimately the maximum number of orders in a wave, the release of the second wave and the moment of change can be defined. An example is shown in figure 24. The maximum should only be set once, as with a lower number of orders the mean and standard deviation of the throughput time will decrease.

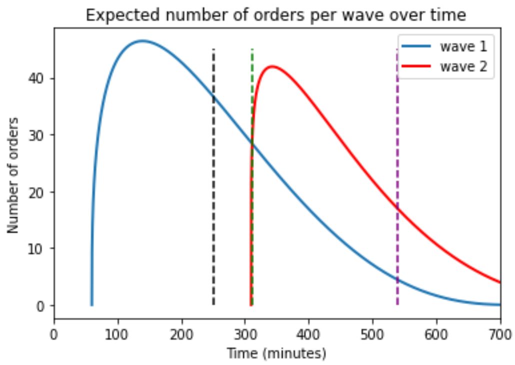

Figure 24: Example system capacity, black line: wave 2 release, green line: wave change, purple line: end of day

Input decision

Y	Minimum fraction of orders sorted at the end of the day of wave 2
X	Maximum fraction of orders not sorted in required wave (overlap area)
$FracO_w$	Fraction of total number of orders handled in wave w
DayStart	Time of first wave release
DayEnd	End of work day

Variables

t = time in the system in minutes

O_w= number of orders in wave w

O_s= number of orders in the system

S = number of orders not sorted in required wave

$f_w(t; \alpha, \beta, a, c)$ Probability densify function (pdf) of the throughput time of wave w

$F_w(t; \alpha, \beta, a, c)$ Cumulative distribution function (cdf) of the throughput time of wave w

The $f_2(t)$ and $F_2(t)$ functions of the second wave are shifted with A (release time of second wave)

Decision variables

$MaxO_s$= Maximum number of orders in the system

$MaxO_w$= Maximum number of orders in wave w

A = release time of second wave

B = moment of wave change

Heuristic:

1) Set an initial value for O_s
2) Compute O_w = $FracO_wO_s$
3) Determine A: A = DayEnd - $F_2^{-1}(Y)$
4) Determine B such that $f_1(t)O_1 > f_2(t)O_2$
5) Determine S: $S = 1 - F_1(B)O_1 + F_2(B)\, O_2$
6) If $S/O_s > X$: decrease the number of orders in the system (O_s), if $S/O_s <= X$: Stop

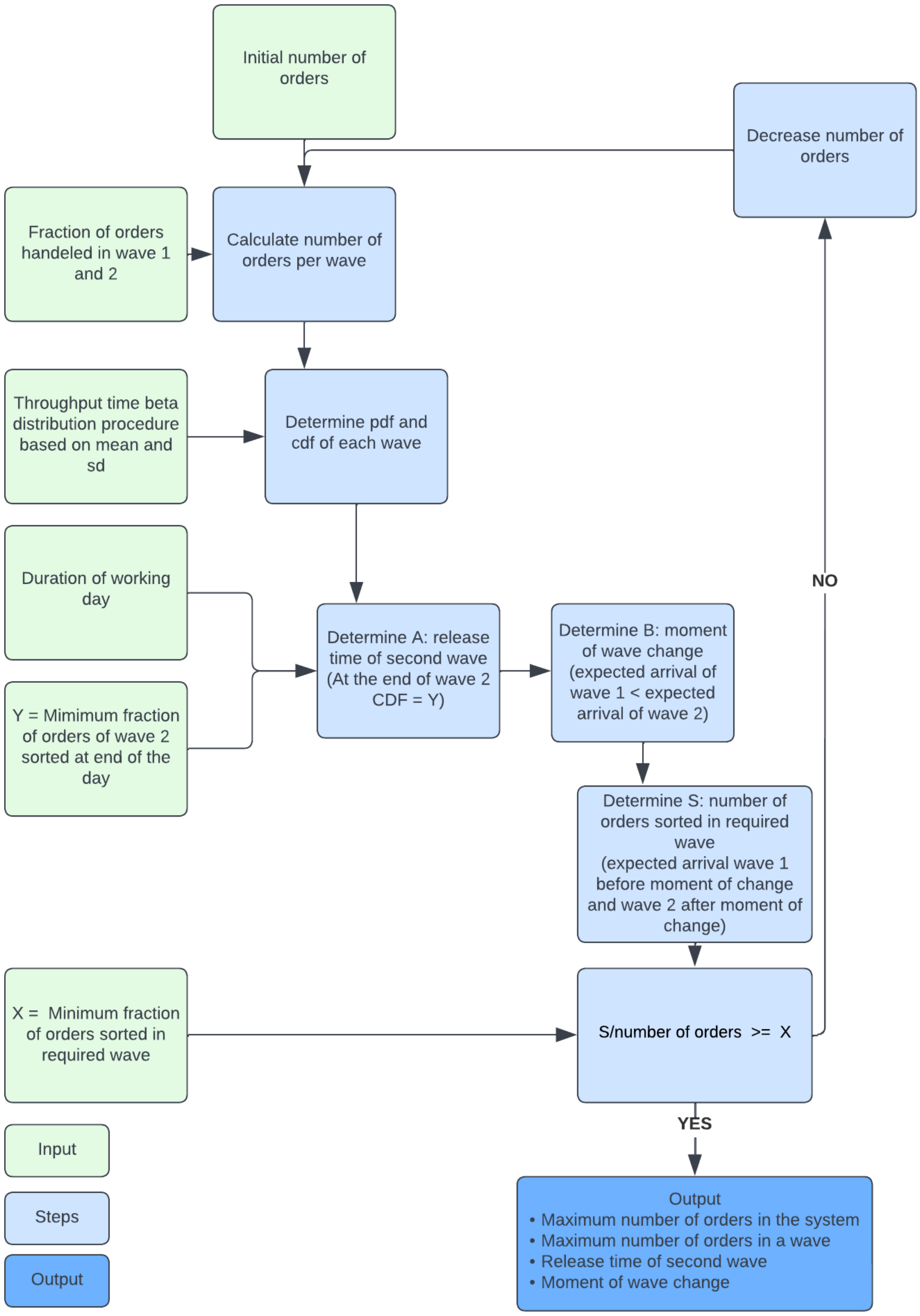

Figure 25: Determination of maximum system capacity

5.3. Simulation model

A discrete event simulation has been developed to evaluate the system performance of the MIQP and determine the system capacity. A discrete event approach models a process as a series of consecutive events. Between the events the system is fixed and not changing. Different types of events can be handled in different ways (Fishman, 2001). This chapter provides the details of the developed simulation model.

5.3.1. Input parameters

Orders: the order information is the same as used as input for the MIQP. However, orders that are processed in the packing area are also included in the simulation model. From the MIQP the order to wave allocation is used as input. The actual arrival time, carrier, volume and packing or non-packing of an order is provided as input to the model.

- Carrier
- Volume
- Arrival time
- Packing or non-packing
- Stochastic throughput time dependent on the mean and variation of the wave throughput time
- Order to wave allocation (From MIQP)

Carrier: Carrier trucks are modelled in the simulation model as separate entities. In de MIP the truck departure is modelled as the order due date, however, due to a varying order warehouse throughput time, orders can end up in another truck. Furthermore, a truck change means that cannot process orders for a fixed period of time. Orders sorted during the truck change end up in the lane queue or are sorted to an internal backup lane.

- Departure time carrier trucks
- Truck change (7 minutes). During the truck changes, orders can enter the external lane queue, until the maximum queue length is reached.
- Carrier-to-lane and wave allocation (From MIQP)
- Maximum truck capacity (50 m^3)

Sortation lane: A sortation lane can process 350 parcels per hour (6 per minute). The conveyor sortation lane can have 12 parcels in the queue before the sortation lane is closed.

- Deterministic queue length external lane (12 parcels)
- Deterministic process rate (6 parcels per minute)

Wave duration: The duration of the wave depends on the wave volume. Figure 8 illustrate a day. Two moments can be separated, the moment the wave batch is released and the moment the sortation ends and the sortation of the new wave starts (sortation change). At the end of the sortation still, parcels can be sorted from the previous wave (as waves will always overlap), however, they will follow the carrier-to-lane allocation of the new wave. The time between wave batch release and wave end is called wave duration.

- Wave release
- Wave sortation start
- Wave sortation end

5.3.2. Simulation process

The simulation model follows the process as visualized in the BPMN diagram in figure 23. The simulation model is designed in minutes.

Order:

1. Order to wave:
    a. Standard orders are assigned to a wave according to the order to wave allocation
    b. Packing orders are assigned to the first wave in which they are available
2. Throughput time:
    a. Standard orders: Depending on the number of orders in the wave the stochastic order throughput time is determined based on the beta distribution.
    b. Packing orders: Order throughput time is assigned based on the beta distribution for packing orders.
3. Sortation time: Wave release time + order throughput time
4. Sortation lane: according to the carrier to wave to lane allocation at the sortation time
    a. Internal lane: directly sorted and loaded
    b. External lane: Check whether the queue is not full, if the queue is full send it to the backup lane
        i. Order waits in the queue and is handled according to the FIFO principle
    c. Backup lane: directly sorted and loaded

External lane queue:

1. Order enters the queue at the sortation time
2. Order is handled according to a fixed rate per minute (6 orders per minute).
    a. If a truck is full, a truck change should be executed the whole queue has to wait the duration of a truck change (7 minutes).
    b. If at the sortation end time of a wave a carrier should change lane (internal to external and vice versa), trucks should switch dock. The queue is closed, parcels in the queue from the previous carrier on the external lane are still finished. Orders of the new carrier can enter the queue, however the orders have to wait to be processed for the duration of a truck change (7 minutes).

Truck:

- Location:
    a. External lane: the truck is allocated to a dock corresponding to the external sortation lane allocation of the wave.
    b. Internal lane: the truck is allocated to a dock where containers and pallets of the internal lane can be loaded.
- Loading: the order arrives, the volume of the parcel is added to the truck load
- Truck change:
    a. When a truck has a full truckload (50 m^3)
        ii. A new truck of the same carrier will dock the lane (7 minutes)
    b. When a truck needs to depart according to the departure time
        iii. A new truck of the same carrier will dock the lane (7 minutes)
    c. When the wave sortation end time is reached and another carrier is allocated to the lane
        iv. A new truck of another carrier will dock the lane (7 minutes)

5.3.3. Model logic

Table 4 summarizes the processes and corresponding events the simulation deals with. Within each event, a set of actions is executed and new events are scheduled. An event can take place at a fixed time (e.g., truck departure, wave release, start wave sortation, etc.) or depends on other events (e.g., the time an order arrives at the sorter depends on the wave release).

Table 3: Overview of discrete events in the simulation model

Process	Event	Description
Order picking	Order arrival at the sorter	The order arrives at the sortation system. The arrival time is determined by the wave release + standard order throughput time.
Order picking and packing	Order arrival at the sorter	The order arrives at the sortation system. The arrival time is determined by the wave release + packing order throughput time.
Wave management	Wave release	The wave batch created with the order to wave allocation is released to the warehouse order pickers. The moment a wave is released is fixed input to the model.
	Start wave sortation (carrier lane change start)	The carriers are allocated to the sortation lane based on the carrier to wave to lane allocation. The moment is determined based on the wave release. Carriers who need to change according to the carrier to wave to lane allocation, start changing trucks at this moment. The start wave sortation time and the carrier-to-lane to wave allocation are fixed inputs to the model.
	End wave sortation	The carrier-to-lane allocation stops for the current wave. The allocation of the new waves starts. The end wave sortation is a fixed input to the model.
	Carrier lane change end	The carrier is located at the right sortation lane. The time is equal to, the carrier-to-lane change start + truck change time.
Internal sortation	Internal lane sortation	The order is sorted on the internal sortation lane. Whether an order is sorted internally is determined on the order arrival time at the sorter and the carrier-to-lane allocation of the wave sorted at that moment.
External sortation	External lane queue arrival	The order is placed in the external sortation lane queue. Whether an order is sorted externally, is determined on the order arrival time and the carrier-to-lane allocation of the wave sorted at that moment.
	External lane queue end	The order leaves the queue. The moment the order leaves the queue is determined by the arrival time in the queue + duration to process the order and all orders that are already in the queue + duration of truck change (if it happens during the time in the queue)
	External lane sortation	The order is sorted on the external lane.
Backup lane sortation	Internal lane sortation	The order is sorted on the internal sortation lane. If an order arrives at the backup lane it depends on the queue length. If the queue is full at the moment of order arrival at the sorter, the order is sorted to the order back up lane.
Truck to dock	Truck arrival at the dock	A truck arrives at the dock. At the start of the day, the moment is equal to the start wave sortation. Afterwards, it depends on the truck departure time and the time needed for a truck change.
	Truck departure	A truck of a carrier departs. This depends on the fixed truck departure time (this is a fixed input to the model) or whether a truck departs earlier when the maximum truck capacity is reached.

5.3.4. Model run documentation

5.3.4.1. Replication length

The replication length is set to one day as the outbound process is a terminating process. The outbound process starts every working day again, by determining which orders belong to which wave. Furthermore, almost every order that is picked will be sorted, which creates an empty system each working day. Orders may have been released by the system, but not yet processed and picked. However, these orders are released again the next day to the system. Because the outbound process is an terminating process and starts with an empty system each day, a warm-up period is not needed.

Furthermore, if a carrier truck is not full enough loaded, it can be decided to not depart during that day. This creates a lower truck capacity on the next slot of a carrier the next day. However, this can be taken into account when assigning orders to a departure date (due date). Moreover, if a carrier does not depart, it will not influence the performance measures in terms of the number of orders sorted internal or external. By setting the replication length to one day, it is assumed that orders, that have a higher sortation arrival time than the end sortation time of the last wave of the day, will be released in the system the next day.

5.3.4.2. Number of replications

To determine the number of replications two methods defined by Robinson (2014) are used. First of all, the graph of the cumulative mean of the performance indicators from a series of replications should be relatively flat (no upward and downtrend and minimum variability. The second method is the confidence interval method, the narrower the confidence interval, the more accurate the results of the model. The number of replications should satisfy inequality 11. Equation 10 is used to compute the confidence intervals. A significance level (α) of 5% is set, for the Student's t-distribution with n-1 degrees of freedom. The mean ($\bar{X}$) and standard deviation (S) needed to determine the number of replications is computed by performing a small initial run.

$$CI = \bar{X} \pm t_{n-1,\alpha/2} \frac{S}{\sqrt{n}} \quad (10)$$

$$n > \frac{100St_{n-1,\alpha/2}}{d\bar{X}} \quad (11)$$

The number of replications will differ per the defined scenario, as in some scenarios some parameters will be variable or not in comparison with others. Therefore, the number of replications is determined per scenario. Furthermore, the computation time per scenario is taken into account. However, the minimum number of replications is set to 5.

5.3.4.3. Validation

If the simulation model is a reasonable representation of a real-world system to people who are knowledgeable about the real system, it can be concluded that the model is face-validated (Carson, 2002). A face to face validation is done by presenting the simulation model to both the operation manager and supply chain manager of vidaXL. Both managers agree the model is a realistic representation of the system for the defined purpose. Furthermore, to develop the model, information has been collected through discussions with planners and other operations employees. Also, the warehouse management system of vidaXL has been used to clarify the system, because it tracks many steps in the process. Furthermore, documentations of the process, as defined by vidaXL, have been used to elucidate parts of the process.

In addition to validating the performance of the simulation, a simulation run is executed with the actual carrier-to-lane to wave allocation, order to wave allocation and wave release time of a day. This simulation run is compared with the actual performance of that day. The day chosen is an single shift working day with 19276 orders divided over 2 waves. The performance of the percentage of orders processed internal and the percentage of orders planned in a wave is measured. The performance of the simulation model is close to the actual performance (difference +/- 1%). Together with the face validation it is concluded the simulation model is an actual representation of the current system operation. Although, it would be beneficial to validate the simulation model with different actual days, however only limited historical data is available for the actual carrier-to-lane to wave and order to wave allocation.

Table 4: Simulation model validation

Performance	**Simulation model (5 replications)**			**Actual**	**Difference**
19276 orders	*Mean*	*Standard deviation*	*Confidence interval*		
Percentage of orders processed on internal lane	27.379%	0.153%	27.190 - 27.569	26.48%	-0.895%
Percentage of orders processed in planned wave	84.003%	0.078%	83.906 - 84.100	85.12%	1.120%

6. Case study

The case study consists of two types of scenarios to answer sub-research questions four and five. Firstly, the model performance on different types of days is measured, by defining scenarios with varying number of orders and working hours (e.g. single or double shift). This will answer sub-research question four: *What are the effects on the warehouse performance for a more dynamic carrier to sortation lane allocation model?* (Section 6.2.). Secondly, the time horizon for the carrier-to-lane to wave allocation is investigated, by defining scenarios in which the planning horizon for the carrier-to-lane to wave allocation varies. This will answer sub-research question five: *What is the most cost-effective and user-friendly planning horizon of the carrier-to-lane allocation method to increase the performance of the sortation process?* (Section 6.3.).

6.1. General experimental setup

System capacity

The case study only investigates a two wave setup, as in a single shift it is the only possible approach and in a double shift it is currently the most often used setup. To determine the time of release of wave 2 and the time of sortation change between wave 1 and 2, the percentage of orders in wave 1 and wave 2, the start time of the day and the end time of the day has to be set. Based on the historic data analyses and discussing with operations, the division between the orders in the waves is set to 60/40 in a single shift and 50/50 in a double shift. Furthermore, the percentage sorted at the end of wave 2 is set to 80% in a single shift and 90% in a double shift. It often happens the resulting orders of wave 2 are finished in overtime with less workers. The percentage of orders not sorted should be set lower in a single shift, because it is otherwise not possible to process the required amount of orders. The same applies for the percentage of orders sorted in the required wave. Moreover, in a single shift, more time is available to work overtime compared to a double shift and the volumes are lower. Following the heuristic defined in section 5.2. the wave two release time and wave sortation change time is computed. In table 5 all input and output values of the system capacity approach can be found. For every single and double shift scenario independent of the number of orders the system capacity settings shown in table 5 are used (e.g. start time of waves, sortation change time are the same for every scenario).

Table 5: System capacity settings case study

	Single shift	**Double shift**
Input system capacity		
Wave 1 release (minutes)	300	180
Start sortation (minutes)	360	240
Workday end (minutes)	840	1200
% of orders in wave 1	60%	50%
% of orders in wave 2	40%	50%
% of orders sorted in planned wave	80%	90%
% of orders planned in wave 2 sorted	80%	90%
Output system capacity		
Maximum number of orders planned	25022	56402
Wave 2 release (minutes)	538	594
Wave sortation change (minutes)	605	726

Experimental setting

A computation run consists of solving the MIQP model followed by a single simulation run based on the outcome of the MIQP. The MIQP model is solved using Gurobi Optimizer in Python. As Gurobi Optimizer is one of the most used and powerful mathematical programming solvers available. To reduce the computational complexity in the MIQP model, orders with the same due date and carrier are bundled in small batches around 5m^3 (cumulative sum closest to 5m^3). The batch size is chosen in such a way that the model can run in an acceptable time on the computers available for the research, while still providing sufficient flexibility to create an optimal allocation of orders to lanes. In the simulation model orders are not batched, because each order has its own stochastic throughput time.

Parameter setting for MIQP

The parameter setting for the MIQP model is shortly discussed below. First of all the sets are defined. Work is always executed in 2 waves ($W = \{1, 2\}$). The number of carriers ($C = \{1, \dots c\}$) depend on the situation; single shift: 36, double shift: 39. The number of lanes should be higher than the number of carriers and is set to 41 ($L = \{1,41\}$). As 18 external lanes are available A_l is set to one for the first 18 lanes. The number of orders ($O = \{1, \dots o\}$) depend on the scenarios. $B_{c,o}$ is also depended on the order. $D_{w,o}$ is determined based on the due date and arrival time of an order as discussed in section 5.1. The due date of the orders are set based on the transport planning, it is assumed possible carrier departing times are the same every day and a truck has a fixed capacity of 50 m^3. The number of used carrier slots is determined by the number of needed trucks, which is based on the expected total parcel volume of a carrier (m^3). When more departing times are available than trucks needed, the slots are selected equally over the day. By selecting the trucks the following conditions are taken into account:

- At least one truck departure for each carrier should be available after the second wave, otherwise no due date can be assigned to orders arriving in the first wave.
- The number of scheduled trucks per carrier with a due date before the end of the second wave should not be higher than the lane capacity of the first wave. Otherwise the MIQP will be infeasible.
- The total number of orders with a due data before the end of the second wave (therefore only allowed in wave 2) cannot be higher than the total capacity of the first wave.

The capacity of a sortation lane depends on the duration of a wave and is determined with equation 12. With the given wave start and end times this results in a capacity of 88m^3 in wave 1 and 85m^3 in wave 2 in a single shift scenario (175m^3 in wave 1 and 171m^3 in wave 2 in a double shift scenario).

$$CAPL_w = durationofsortationwave * ordersperlaneperminute * meanvolumeoforder \quad (12)$$

The capacity of a wave is determined based on the fraction of orders in a wave and the total expected volume of orders at the start of the day. 50 m^3 is added to the total volume of orders to allow some flexibility in assigning orders to waves.

$$CAPW_w = (totalvolumeofordersonday + 50) * fractionofordersinwave \quad (13)$$

As discussed in the section 3.4. the additional costs for using an internal lane are reported in minutes and are set to 13.34 minute (C^I= 13.34).

Each carrier is assigned a preference ($PC_{c,l}$) of value 0 to one external sortation lane and a preference of 0.4 to another external sortation lane. For all other lanes the value is set to 1. Each external lane has almost the same number of carriers with a 0 or 0.4 value. If a lane has more 0 or 0.4 values it is taken into account that these are the carriers that have a low expected volume. The preference to allocate an order to a wave ($PW_{w,o}$) is set to zero in the first wave the order is allowed and 0.5 in the second wave the order is allowed. If the order is only allowed in one wave, the preference is set to zero.

Input data generation

Only a limited sample of data is available. Therefore bootstrapping is used, to create samples of order data for each scenario and to model unpredictable variability of the orders. According to Robinson (2014) it is a good method to use as only limited data is available. By doing so it allows to investigate more scenarios. The bootstrapping approach is used in two ways:

For the dynamic carrier to sortation lane allocation scenarios four datasets are created. A single shift dataset divided in packing and non-packing orders and a double shift dataset divided in packing and non-packing orders. For each scenario a total number of orders is defined. All datasets contain order lines with the carrier number, volume and arrival time. Given the number of orders and the type of shift, 97% of the orders is drawn by bootstrapping from the non-packing dataset and 3% is drawn by bootstrapping from the packing order set.

For the planning horizon scenarios the number of orders per carrier per day is given as input. Therefore, a dataset is created per carrier divided in packing and non-packing orders. Only double shift data is used, as the scenario only investigates a double shift period. The dataset contains order lines with the volume and arrival time of an order. Given the number of orders and the carrier, 97% of the orders is drawn by bootstrapping from the non-packing dataset and 3% is drawn by bootstrapping from the packing order set.

6.2. Scenarios dynamic carrier to sortation lane allocation

The scenarios in table 6 are defined to examine how the dynamic carrier to wave to lane allocation model performs under different conditions compared to a static carrier to wave to lane allocation model. The order data are created by bootstrapping as discussed in section 6.1. To exclude the influence of forecasting errors, it is assumed all order information is known at the start of the day, this means the arrival time is known. However, an order is still not allowed in a wave if the order arrival time is higher than the release time of the wave. For every scenario 5 samples are created and solved by the MIQP model, followed by a single simulation run.

The scenarios of the dynamic carrier to sortation lane allocation model are compared with the performance of a static lane allocation (e.g. no changes between lanes during the day). The static lane allocation is determined by allocating the 18 carriers with the highest volume (m^3) to each wave. The same samples are used and orders are allocated to a wave with the use of MIQP model with a given lane allocation resulting in a MILP model (Appendix 6), followed by a single simulation run.

Table 6: Scenarios dynamic carrier to sortation lane allocation

↓Day type →Shift type	**Single shift (non-packing orders)**	**Double shift (non-packing orders)**
Low	15000	30000
Normal	20000	40000
High	25000	50000
Growth	30000	60000

6.3. Scenarios planning horizon

To investigate the influence of the planning horizon of the carrier to wave to lane allocation on the performance of the sortation area, several planning horizon scenarios are defined. Namely, monthly, weekly, daily and updated during the day. In the monthly scenario the carrier to wave to lane allocation is determined once by the MIQP, using the forecasted volume per carrier per day at the start of the month. The forecast of the orders that arrive between the release of wave one and the release of wave two is determined by multiplying the volume of each carrier at the release of wave one with 1.19.

In the weekly scenario the carrier to wave to lane allocation, is determined every week, using the forecasted volume per carrier per day at the start of the week. The order to wave allocation is done daily based on the orders available at the start of the day and the forecasted orders still to arrive before the start of wave two. The order to wave allocation at the start of the day is done with the use of the MILP model (Appendix 6). Orders that arrive after the start of wave one are allocated to wave two.

In the daily planning scenario, the carrier-to-lane to wave allocation is determined with the use of the MIQP model based on the actual available orders at the time of release of wave one and the number of orders that are forecasted to arrive before the start of wave two. Orders that arrive after the start of wave one are allocated to wave two. In the updated during the day scenario the same method as the daily scenario is used for wave one. Before the second wave the carrier-to-lane allocation is determined again with the use of the MIQP model based on the orders that are allocated to wave two at the start of the day and the orders that are arrived since the release of wave one.

To investigate the scenarios a period in high season (double shift) with 25 working days is selected with an mean of 40940 orders a day and with a standard deviation of 5857 orders. The orders per carrier per day are known, based on this the order information is bootstrapped for each day as discussed in section 6.1. The bootstrapped days are used for each scenario. For each day and scenario, the daily allocation decisions are solved followed by a single simulation run. The monthly and weekly forecasts used are the actual forecast by vidaXL used in this period. The performance of the daily, weekly and monthly forecasts used in the chosen period can be found in Appendix 8.

Table 7: Scenarios planning horizon

	MIQP model		***MILP model***	
Scenarios	*Decisions:* $Y_{w,o}$, $X_{w,c,l}$		*Decision:* $Y_{w,o}$	
	Executed in time period	*Moment*	*Executed in time period*	*Moment*
Monthly	1	Start of the month	25	Start of working day
Weekly	5	Start of the week	25	Start of working day
Daily	25	Start of working day		
Updated during day	50	Start of every wave		

7. Results

Chapter 7 presents and discusses the results of the case study and sensitivity analysis.

7.1. Dynamic carrier-to-lane to wave allocation

In this section for each scenario of the case study the performance of the dynamic carrier-to-lane to wave allocation model (MIQP) and the performance of the static carrier-to-lane to wave allocation model (MILP) is reported. Furthermore, the actual performance (according to the simulation model) is visualized when the dynamic model is provided as input and when the static model is provided as input. The performance of the simulation model is only computed on the non-packing orders, to make it comparable to the carrier-to-lane to wave allocation model (MIQP or MILP). Furthermore, only the orders that are handled before the end of the day are taken into account to compute the performance of the simulation model. Confidence intervals are computed according to equation 10 with a significance level (α) of 5%.

7.1.1. Sortation lane changes during day

Figures 26 and 27 show the number of sortation lane changes between the two waves for the single shift and double shift scenarios. The number of lane changes is an important measure as, each change causes additional complexity for the floor operation. The number of lane changes is always around 13 in all single shift scenarios and no difference can be concluded. The double shift scenario shows an increase in the number of lane changes when the number of orders increases. However, based on the confidence intervals, it can only be concluded that the number of planned lane changes is higher if 60000 orders are handled compared to 30000 and 40000 orders.

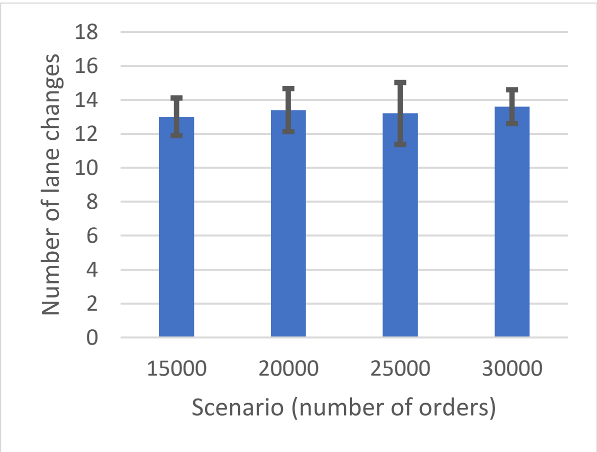

Figure 27: Single shift: number of sortation lane changes between waves

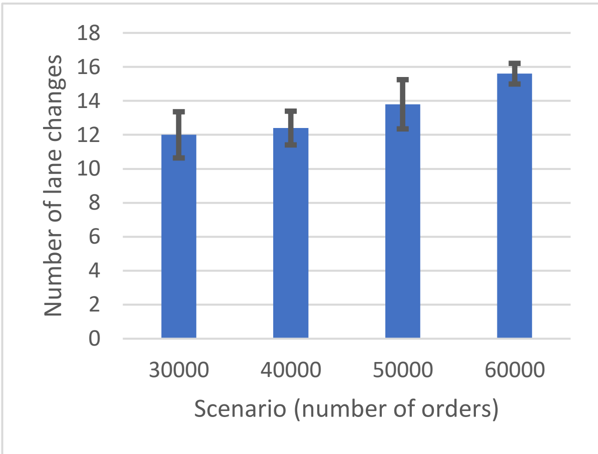

Figure 26: Double shift: number of sortation lane changes between waves

7.1.2. Percentage of orders handled via the internal lane

Figures 28 and 29 show the percentage of volume handled via the internal lane during the day for respectively single and double shift scenarios. In each scenario a dynamic allocation policy (MIQP) performs better (a lower percentage) than the static allocation policy (MILP). However, the difference between the static and dynamic allocation policy becomes lower when the number of orders increases. The double shift scenario with 30000 orders shows a lower performance than the other double shift scenarios. This is caused by a lower percentage of orders handled in the planned wave: 90.6% compared with 92.3% (40000 orders), 92.0% (50000 orders) and 90.3% (60000 orders). The lower percentage of orders handled in a wave is caused by the fixed wave release time of wave 2 and the fixed wave sortation change time for each scenario. The performance may be higher if these times are determined for each number of orders separately, with the use of the system capacity heuristic.

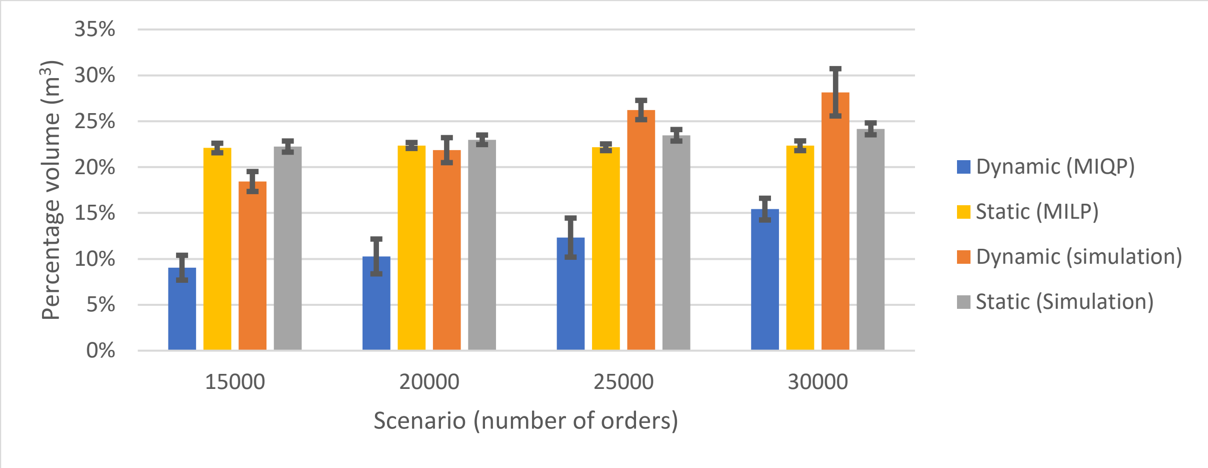

Figure 28: Single shift: percentage of volume of orders via internal sortation lane

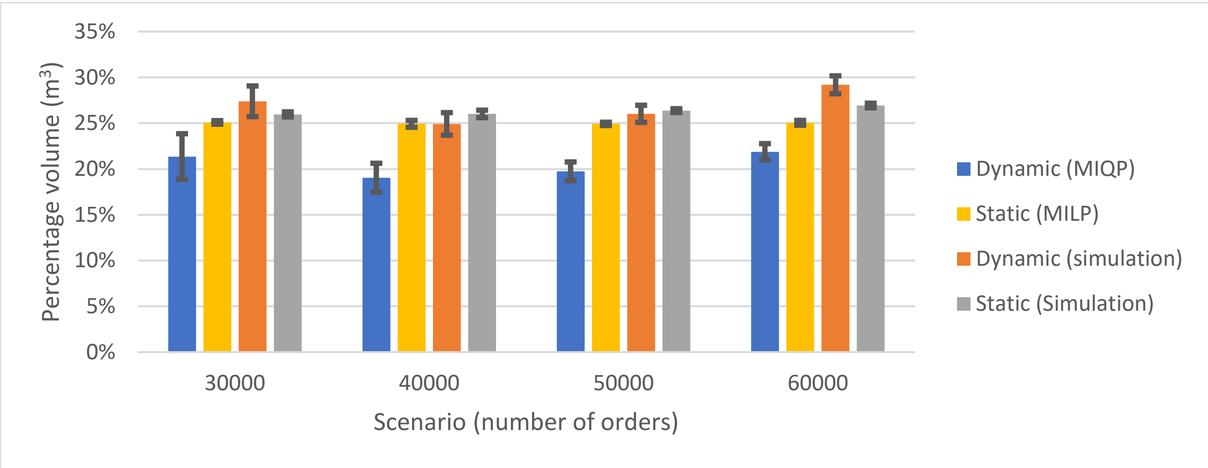

Figure 29: Double shift: percentage of volume of orders via internal sortation lane

Overall the dynamic allocation model (MIQP) performs better than the static allocation model (MILP). However, the relative benefit is smaller when the number of orders increases. Potentially caused by a larger volume per carrier: when the number of orders increases, more carriers will have a higher volume than the lane capacity available in one wave. For these carriers, part of the orders should be planned in a different wave, either on an internal lane (if the volume is low) or on an external lane (if the volume is high). Furthermore, the due dates of orders have an influence on the carrier division over the waves. Orders are assigned to the first departing truck of each carrier. If the number of orders increases the utilization of the trucks departing after the first wave increases (more orders are assigned to the trucks). Resulting in a higher percentage of orders with a due date directly after wave one and therefore only allowed to handle in the first wave. This gives the dynamic allocation model less freedom to optimally allocate orders to waves and thus reduce the usage of the internal lane, as a larger part of the orders is already fixed for the first wave.

When comparing the actual performance through simulation, the static allocation outperforms the dynamic allocation or no clear difference can be found. Only in case of a single shift day with 15000 orders the dynamic allocation policy outperforms the static allocation policy. This is mainly caused due to the overlapping arrival of the orders in a wave at the sortation system. If the required percentage of orders sorted in the planned wave, were set higher when determining the system capacity, the results of the actual dynamic performance would behave more towards the results of the dynamic allocation model (MIQP). The difference between the performance of the static model and the actual performance of the static model is small, as the 18 external lanes are occupied by the same carrier during all the waves. The overlap of the waves therefore, does not cause orders planned on the external lane to be sorted into the internal lane. The only difference between the performance of the static model and static simulation model is caused by orders that are handled internal due to full external lane queues and truck changes. The same would apply to the dynamic model if it were ensured that there is no overlap between the waves.

7.1.3. Additional sortation time internal sortation lane

Figures 30 (single shift) and 31 (double shift) show the total additional minutes spent to the orders processed on the internal lane compared to when an order is handled on the external lane. The results show the same trend as the percentage of orders handled via the internal sortation lane. Overall it can be concluded the dynamic allocation model will not save handling costs (in terms of working minutes), when it is implemented with the percentage of wave overlap defined in the case study. If the solution is implemented and it can be ensured that the sortation process of the waves does not overlap, the saved handling time, depending on the scenario, is equal to 2 to 5 workers a day (8 hour working day).

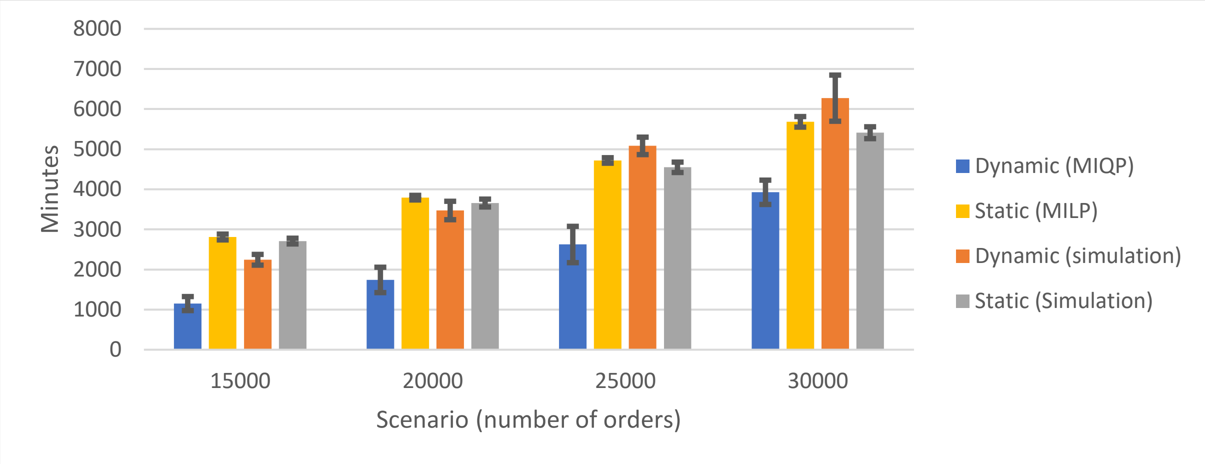

Figure 30: Single shift: additional minutes spent on internal sortation lane

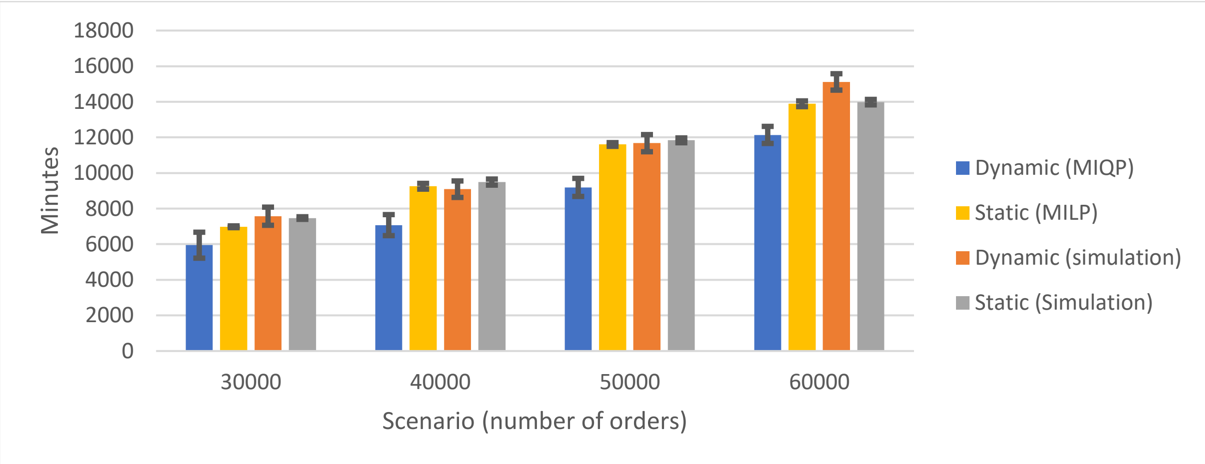

Figure 31: Double shift: additional minutes spent on internal sortation lane

7.1.4. Handling of orders in planned wave

Figures 32 and 33 show the percentage of the volume of the orders handled in the required wave. The percentage of orders sorted in the required wave is in line with the computation of the system capacity heuristic with a fixed release time of wave 2, fixed sortation change time and a fixed division of orders between the waves (Table 8). Small differences occur between the expectation and outcomes due to the system computation is based on the number of orders and the average volume of a standard parcel. Also, the division of volume between the waves is not exactly the same, because to each wave 25m^3 additional capacity was added in the MIQP and MILP. The results of the dynamic model (MIQP) and static model (MILP) shown in figure 32 and 33 are based on the computation of the system capacity, however it takes into account the actual number of orders allocated to the waves.

Table 8: Expected percentage of orders sorted in planned wave

Scenario	**Single shift**				**Double shift**			
	15000	20000	25000	30000	30000	40000	50000	60000
% of orders sorted in planned wave	88%	84%	80%	75%	91%	92%	91%	89%
% of orders planned in wave 2 sorted	89%	85%	80%	75%	99%	97%	93%	88%

Overall, the trend is the higher the number of orders, the lower the percentage of the volume sorted in the planned wave. With one exception, the percentage of volume that is sorted in the required wave is lower in the double shift scenario of 30000 orders compared to the other double shift scenarios. Due to the early start time of wave 2 and the low number of orders, many orders of wave 2 are already processed according to the throughput time distribution, before the wave change is executed. A logical effect is that the percentage of orders planned and sorted in the second wave is lower than in the other scenarios. In the scenario of 30000 orders it would have made more sense to switch the waves sortation earlier and or start the second wave later. However, in the case study it is assumed the sortation change time between waves is fixed and the same for each scenario.

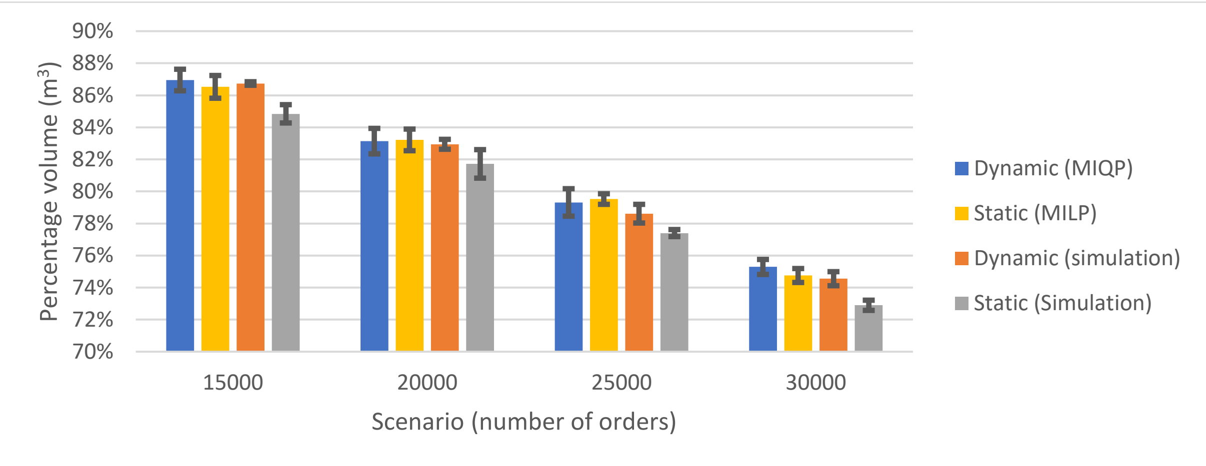

Figure 32: Single shift: percentage of volume handled in planned wave

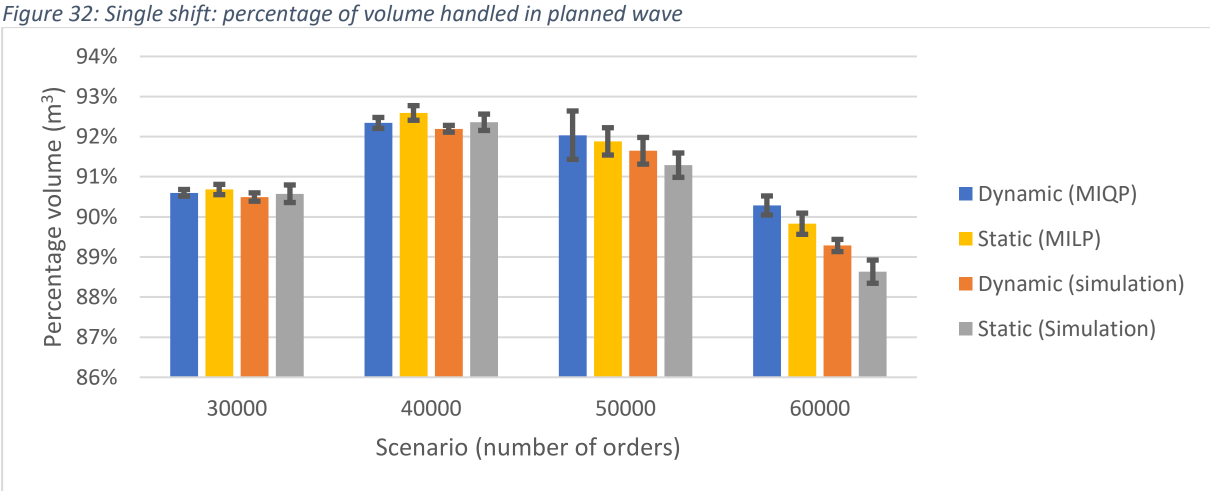

Figure 33: Double shift: percentage of volume handled in planned wave

Figure 34 (double shift) and 35 (single shift) show the percentage of the total volume that is not sorted at the end of the day. The increase is in line with the expectation, if the number of orders increases the throughput time distribution tail will be wider at the end of the working day.

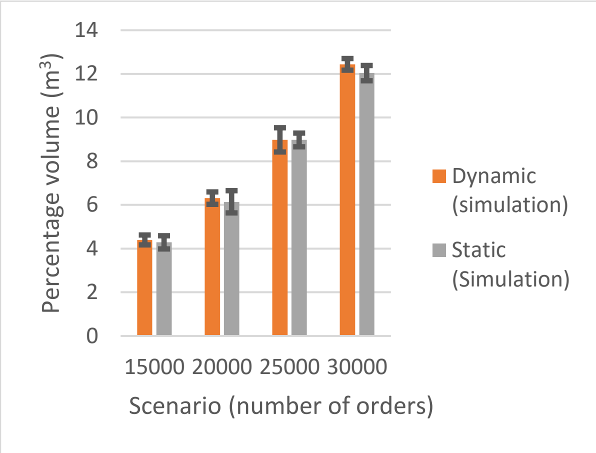

Figure 35: Single shift: percentage of volume not handled

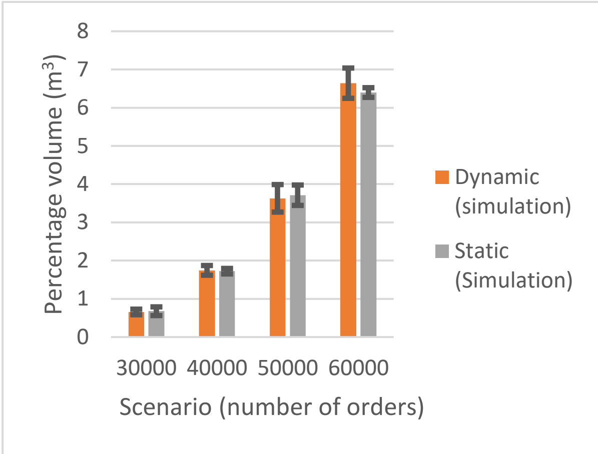

Figure 34: Double shift: percentage of volume not handled

7.2. Planning horizon

In this section the performance of the dynamic allocation model (MIQP) and the simulation model is reported for each planning horizon scenario defined in the case study. The performance is computed in the same way as discussed in section 7.1.

7.2.1. Sortation lane changes during day

Figure 36 shows the average number of sortation lane changes during the day, in each planning horizon scenario. If the dynamic carrier-to-lane to wave allocation is determined daily or updated during the day the number of sortation lane changes is lower compared to a weekly or monthly time frame. A daily allocation with or without update during the day can therefore prevent unnecessary changes. A monthly and weekly planning horizon bases the allocation on a forecast, which is the same for every day and does not take into account daily influences and fluctuations of countries and or carriers, resulting in changes that are not necessary. On a daily basis, a large part of the order information is already known, which already shows an indication of the order volume of each carrier.

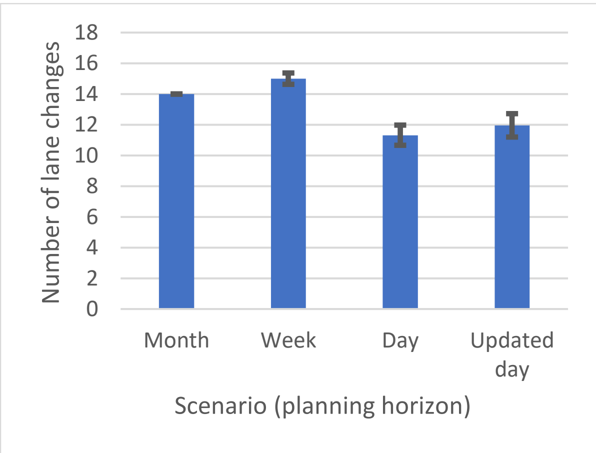

Figure 36: Planning horizon: number of sortation lane changes between waves

7.2.2. Percentage of orders handled via the internal lane

Figure 37 shows that the dynamic allocation model (MIQP) performs better when it is determined daily or updated during the day, compared to the weekly or monthly horizon. On average 2 to 4 percent on a daily horizon and 5 to 7 percent when updated during the day. From the actual performance (simulation) it can only be concluded that an updated allocation during the day performs a little better than a weekly updated allocation, on average 6 percent. The mean of the week horizon is the highest, this is potentially caused by the forecast, as the weekly forecast often fluctuates and does not perform good, according to vidaXL managers. The forecast error over the simulated period per carrier is measured (Appendix 8). Overall, the weekly forecasts shows an equal or even a little higher forecast error compared to the monthly forecast.

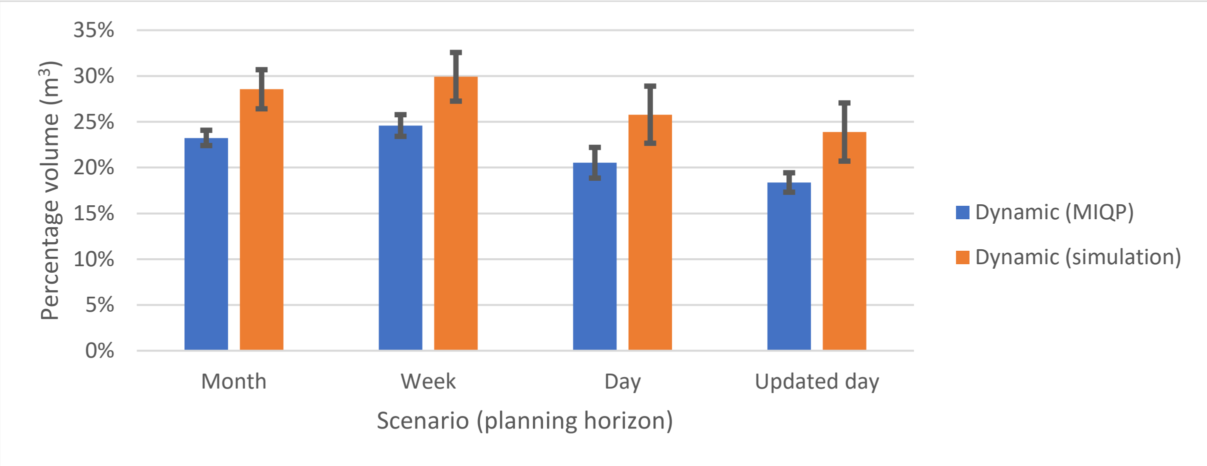

Figure 37: Planning horizon: percentage of volume via internal sortation lane

7.2.3. Additional sortation time internal lane

In figure 38 the additional sortation time of orders handled on the internal lane compared to the external lane is shown for the dynamic allocation model and the simulation model. The actual performance shows that updating the allocation during the day performs better than the weekly allocation. On average the handling time saved is equal to 3 to 4 workers (8h a day). Looking at the performance of the dynamic allocation model, in case the waves do not overlap, determining the allocation daily or update during the day outperform the weekly and monthly horizon. This would results in a handling time saving that is on average equal to 2 to 4 workers.

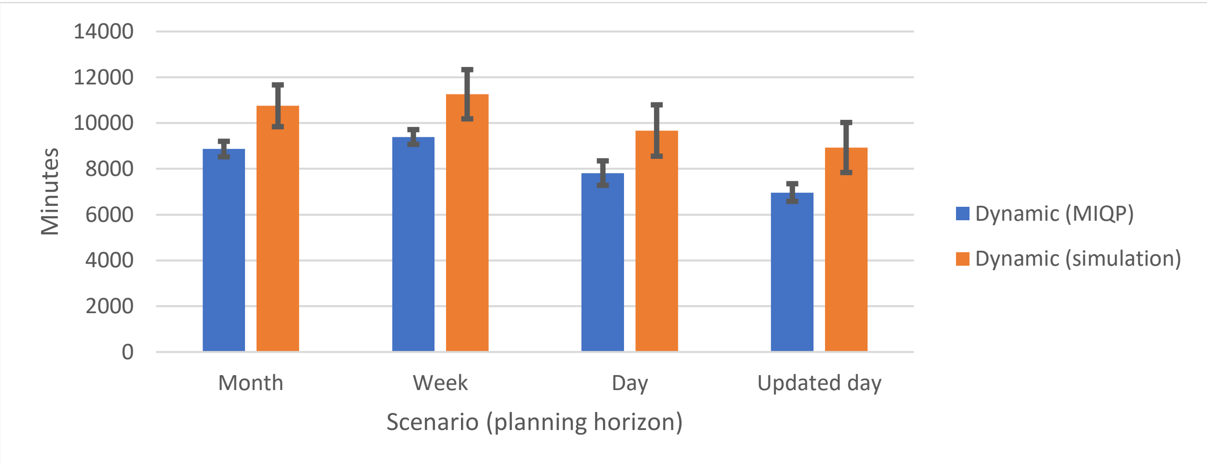

Figure 38: Planning horizon: additional minutes spend on internal sortation lane

7.3. Varying system capacity

In the case study the release time of wave 2 and sortation change time were fixed, based on the maximum number of orders that can be handled given the required percentage of orders sorted in the planned wave and the required percentage of orders planned in wave 2 that are actually sorted. This section shows how the number of orders that can be planned in a day is affected by the required percentage of orders sorted in a planned wave and the percentage of the orders of wave 2 sorted at the end of the day.

Table 8 and 9 show the results for the single shift and double shift. An increase in the percentage of orders sorted in the planned wave effects the total number of orders more than the same increase in the percentage of orders sorted planned in wave 2. Changing the percentages has also an influence on the start time of wave 2 and the sortation change between the two waves, the outcomes can be found in Appendix 7. Logically, when increasing the percentage of orders to be sorted at the end of wave 2, the release time of wave 2 will be earlier. Changing the percentage of orders sorted in a planned wave will affect the sortation change time between the waves. Furthermore, the results show that when more working hours are available the percentage of orders sorted in a wave can be higher, while the number of orders processed in a hour is the same.

Table 9: Single shift: maximum number of planned orders in a day with different system capacity settings with a 60/40 division between wave 1 and 2.

→: % of orders sorted in planned wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders planned in wave 2 sorted						
95%	N/A	N/A	N/A	15144	17477	19792
90%	N/A	N/A	16761	19524	22167	24934
85%	N/A	16199	19581	22554	25484	28595
80%	N/A	18301	21843	25022	28208	31605
75%	15193	20100	23802	27182	30600	34253
70%	16648	21712	25575	29151	32789	36680

Table 10: Double shift: maximum number of planned orders in a day with different system capacity settings with a 50/50 division between wave 1 and 2.

→: % of orders sorted in planned wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders sorted at end of wave 2						
95%	41873	49785	56377	62634	68953	75601
90%	47674	56403	63702	70631	77619	84950
85%	51792	61136	68967	76402	83894	91737
80%	55192	65067	73359	81234	89164	97454
75%	58202	68568	77287	85573	93913	102624
70%	60983	71820	80953	89637	98379	107509

In the case study the input of the percentage of orders sorted in the planned wave and the percentage of orders planned in wave 2 that are sorted at the end of the day was set as a minimum requirement. When the number of orders is lower than the maximum number of orders determined, the both input percentages will be higher or at least the same. However, if one of the two input percentages is more important, it can also be chosen to determine the release time of wave 2 and sortation change time, for every number of orders. Given a minimum percentage of one of the input percentages and the number of orders, the release time of wave 2 or the sortation change time can be computed for the highest possible value of the other input percentage. For example, if the percentage of orders sorted in a planned wave is most important, the minimum percentage of orders planned in wave two and sorted on time can be set to a fixed percentage. The most optimal sortation change time can be computed for the percentage of orders to be sorted in planned wave. The result of this example is that the performance of the internal sortation lane improves as the wave overlap is reduced.

7.4. Sensitivity analysis

An sensitivity analysis is performed on the dynamic allocation model (MIQP), when parameters are changed. The analysis is carried out on four parameters: the due date of an order, the number of waves, the number of sortation lanes and the number of carriers. The setup of each analysis and its impact on the performance is discussed in the following sub-sections.

7.4.1. Due date (percentage of orders only allowed in first wave)

The due date (carrier departure time) of an order determines in which wave the order is allowed. An order is only allowed in a wave before the wave in which the due date expires, indicated with $D_{w,o}$ in the dynamic allocation model. In case of a two wave strategy, orders from which the due date expires in wave 2 should be handled in wave 1. The volume of those orders is only allowed in the first wave. The volume of orders only allowed in one wave cannot exceed the capacity of a wave, as the model would be infeasible. However the smaller the number of orders that is only allowed in one wave, the higher the freedom of the model to optimally allocate orders to a wave and thus reduce the use of the internal lane. The effect of the percentage of the total volume of orders a day only allowed in the first wave on model performance is tested: on a single shift day with 25,000 orders (1599m^3), 36 carriers, 18 external sortation lanes and a sortation capacity of 60% (989m^3) in wave 1 and 40% (660m^3) in wave 2. For each scenario, given the percentage of the total volume of orders a day only allowed in wave 1, the due dates are divided randomly over all orders. All other conditions are kept the same.

In figure 40, it can be observed that the percentage of volume sorted to the internal lane increase when the percentage of volume, allowed only in the first wave, increases. In case all volume is allowed in every wave the performance of volume sorted to the internal lane could be minimized to 8%. Conversely, if the volume of orders only allowed in a wave is almost equal to the wave capacity the usage of the internal lane can only be minimized to 31%. The same pattern applies to the additional handling minutes spend on the internal lane (figure 39). Furthermore, from figure 41 it can be observed that if the freedom of allocating orders to waves is reduced, the number of lane changes decreases. Because it becomes less possible to allocate almost the complete volume of a carrier to a single wave.

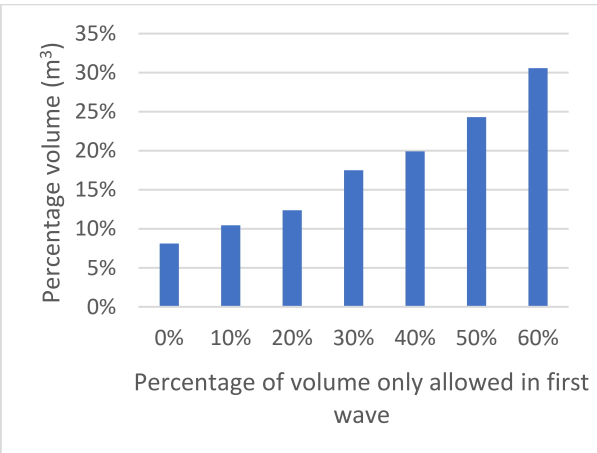

Figure 40: Percentage of volume of orders via internal sortation lane (Sensitivity due date)

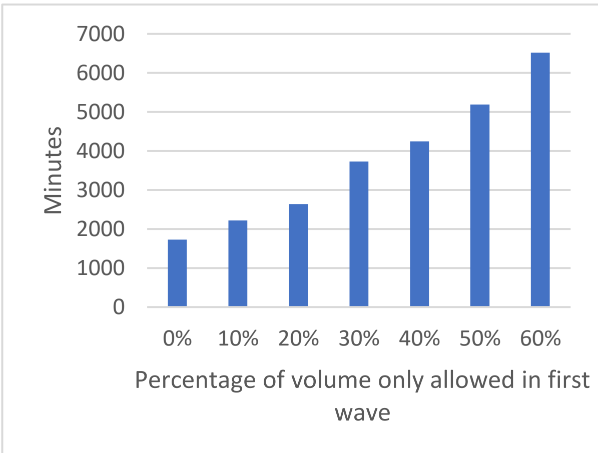

Figure 39: Additional minutes spent on internal sortation lane (Sensitivity due date)

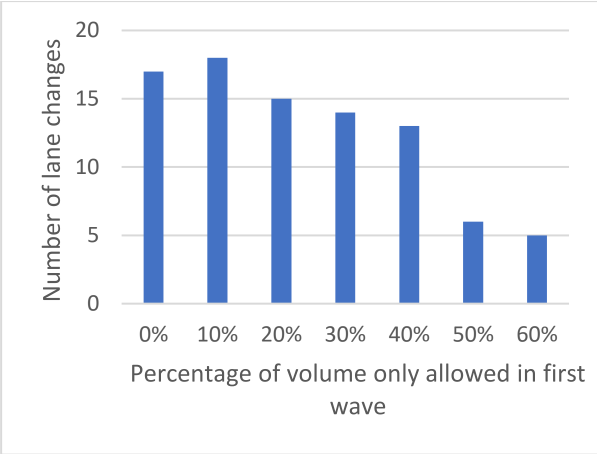

Figure 41: Number of sortation lane changes between waves (Sensitivity due date)

7.4.2. Number of waves

The number of waves during a day determines how often the sortation lanes can be changed. The effect of the number of waves on the performance of the MIQP model is analyzed in this section. The analysis is carried out for a two, three and four wave strategy on a double shift day, with 50,000 orders (3,496m^3), 18 external sortation lanes and 39 carriers. For each wave strategy the duration and maximum volume of a wave is equally divided over the waves. All other conditions are kept equal.

Figure 42 and 43 show that an increase of the number of waves, result in less orders sorted on the internal lane and less additional handling time. However, in a situation in which the sortation of waves overlap, an increase in the number of waves, would cause a decrease in performance as more overlapping periods would take place. If the number of waves increase, the moments to change sortation lane allocation increase and therefore the number of lane changes increases (figure 44). However, the number of lane changes per moment to change is the highest in a three wave scenario.

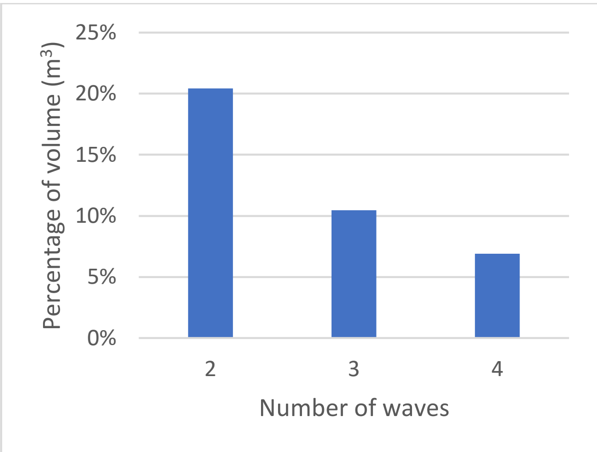

Figure 43: Percentage of volume of orders via internal sortation lane (Sensitivity waves)

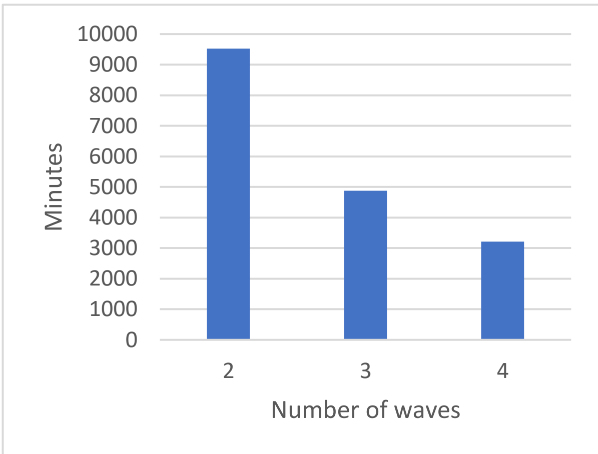

Figure 42: Additional minutes spent on internal sortation lane (Sensitivity waves)

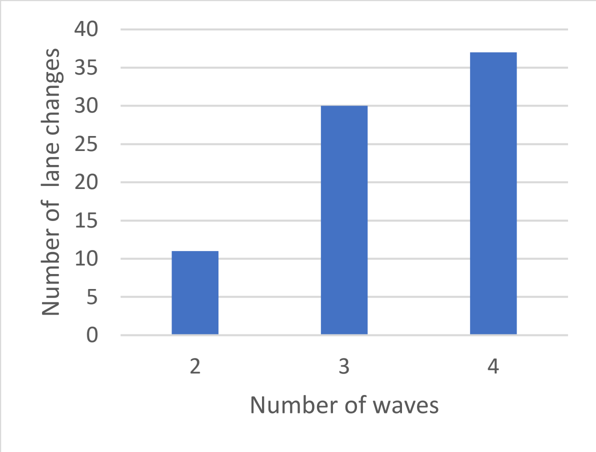

Figure 44: Number of sortation lane changes between waves (Sensitivity waves)

7.4.3. Number of external sortation lanes

The number of external sortation lanes would affect the performance of the dynamic allocation model, as less carriers will compete for one position at an external lane. To test the influence of the number of external lanes an analysis is carried out on a double shift day, with 50,000 orders (3,496m^3), 39 carriers, 2 waves and a sortation capacity of 50% (1773m^3) in both waves. The number of lanes vary between 15 and 35, all other conditions are the same in each scenario. The results show a lower use of the internal sortation lanes as the number of external sortation lane increases.

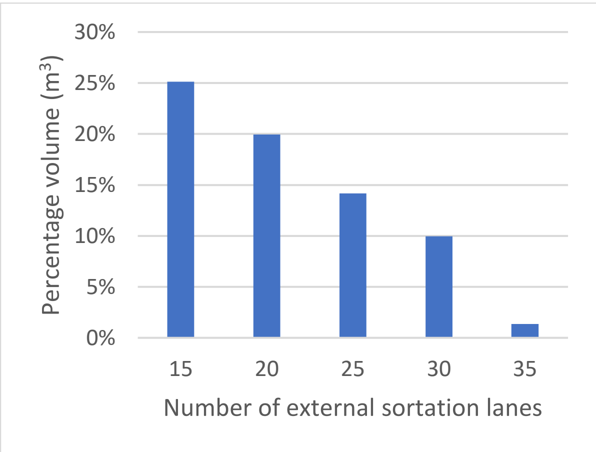

Figure 46: Percentage of volume of orders via internal sortation lane (Sensitivity lanes)

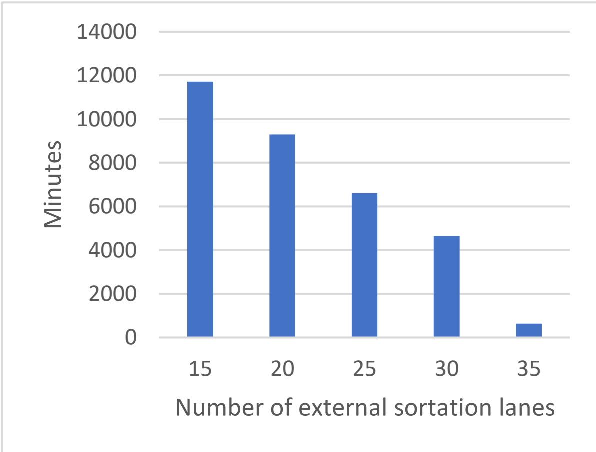

Figure 45: Additional minutes spent on internal sortation lane (Sensitivity external lanes)

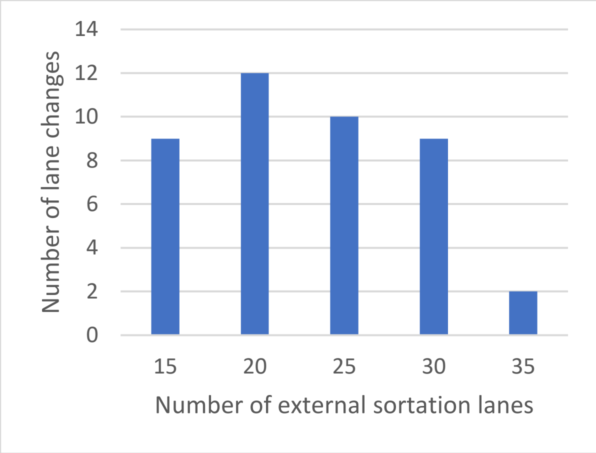

Figure 47: Number of sortation lane changes between waves (Sensitivity lanes)

7.4.4. Number of carriers

The number of carriers would affect the performance of the dynamic allocation model, if the number of carriers increases and the volume remains constant, more carriers with lower volumes compete for an external sortation lane, resulting in carriers with a lower volume sorted on the external sortation lane. The analysis is carried out on a double shift day, with 50,000 orders (3,496m^3), 18 external sortation lanes, 2 waves and a sortation capacity of 50% (1773m^3) in both waves. The number of carriers vary between 20 and 60, orders are assigned randomly to the carriers in each scenario. All other conditions are the same in each scenario. Figures 48 and 49 show that the percentage of volume handled through the internal lane and the additional handling time increases as the number of carriers increases. Because the total volume is constant, on average the volume per carrier is lower.

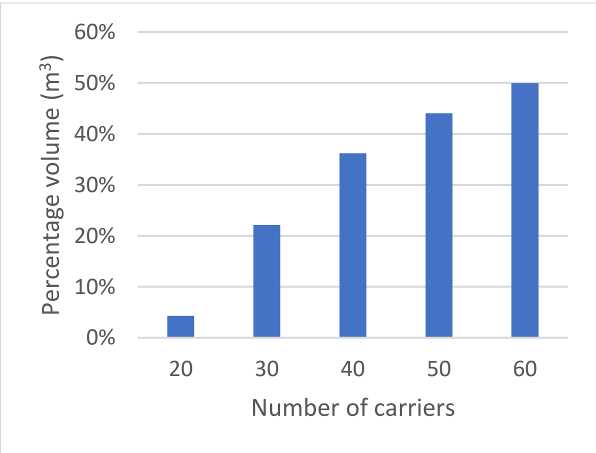

Figure 49: Percentage of volume of orders via internal sortation lane (Sensitivity carriers)

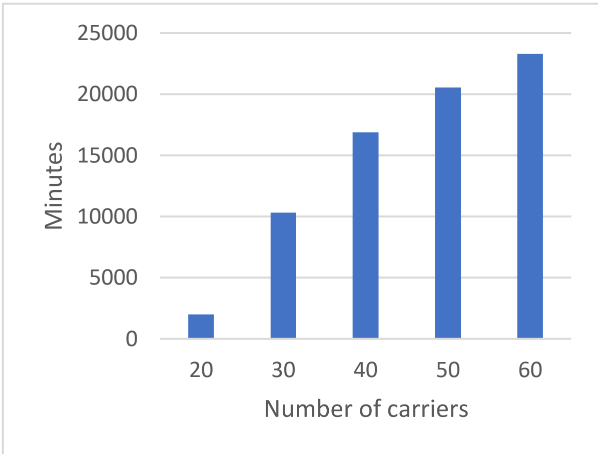

Figure 48: Additional minutes spent on internal sortation lane (Sensitivity carriers)

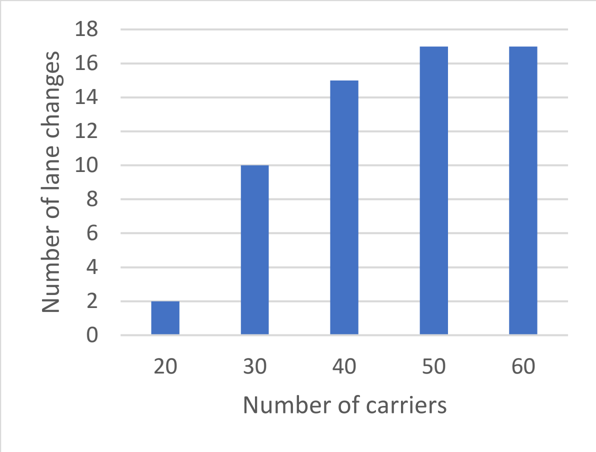

Figure 50: Number of sortation lane changes between waves (Sensitivity carriers)

7.5. Discussion

The case study was intended to gain insight into the influence of a dynamic carrier-to-lane allocation on different planning horizons. In this section, the results of the case study and sensitivity analysis are discussed and highlighted.

Based on the results presented, it can be seen that the dynamic carrier-to-lane allocation can increase performance in terms of less orders sorted to the internal sortation lane. 16 to 40 hours additional handling time on sortation can be saved. However, these benefits are limited and only applicable if it is ensured that waves do not overlap or only overlap to a very limited extent. Reducing the overlap of the waves, by waiting to pick the new wave until the previous wave is completed, affects the picking performance, because pickers who completed their picking task remain inactive until all tasks of a wave are completed. The throughput time analysis and the beta distribution show that the tail of a wave is long, which means that waiting till the wave is completed will take a relatively long time. A later release of the next wave, means that additional picking time is needed to process the same volume in the next wave and consequently the total picking time in a day increases. The number of hours that can be saved on additional sortation time by separating the waves is low compared to the number of scheduled order pickers. Therefore, if the next wave is released at a time the previous wave is (almost) finished, it is likely that the additional picking time will be higher than the time saved with sortation. For example, on a day with 30000 orders, 47 order pickers are planned, possibly 29 hours of additional sortation time can be saved when waves do not overlap. Moreover, releasing the next wave later, would also lead to a lower throughput of parcels at the sortation lanes and thereby more total sortation time in a day.

A reduction in wave overlap by delaying the picking process cause a decrease in picking efficiency. Therefore, it would be interesting to investigate other methods that can ensure a separation in the sortation of the waves. Possible practical solutions can be to label the pick containers with the wave number, so that at the loading station of the sortation system, the workers who load the parcels on the sortation system can give the previous wave an advantage over the other wave. Furthermore, starting the sortation process a few hours later than the picking process, creates a buffer at the sortation loading station. A buffer, where the stored parcels can be clearly separated per wave, would cause more parcels of the first wave to be sorted before the sorting the second wave starts. Buffering can also result in a more steady flow of parcel on the sortation system. However, buffering requires storage capacity on the floor and containers for picking will be less likely to be available for a new picking round. Moreover, the overlap of the waves can possibly be reduced by adjusting the breaks schedule of the workers of the different teams (sortation and picking).

Due to the limited benefits of the dynamic allocation compared to the static allocation or even a lower performance in case of the suggested percentage of wave overlap, it is doubtful whether a dynamic allocation policy should be implemented in the simulated situation. The dynamic allocation policy results in many sortation lane changes with limited performance increase. These sortation lane changes cause additional complexity on the floor, workers cannot learn the topography of the carrier allocation. To make the allocation of carriers to lanes clear to workers, currently signs with the carrier name are located next to the sortation lanes. When a dynamic allocation is introduced these signs must be switched manually or an investment in digital signs must be made. A carrier lane change also means that the carriers have to change dock, which causes additional truck changes. Furthermore, it must be ensured that the sortation lane and staging area of the dock are completely empty before the carrier lane allocation is changed, otherwise parcels will end up in the wrong carrier trailer.

Moreover, the developed dynamic carrier-to-lane allocation model schedules sortation lane changes between waves for the smallest advantage in volume that is not handled on the internal sortation lane. The number of lane changes may be reduced when a minimum threshold volume for a lane change is set.

In the case study, a fixed wave release time and sortation change time are computed once based on the maximum number of orders. Instead, determining the wave release time and sortation wave change time daily based on the number of orders in each wave and the expected throughput time of the waves, may result in a better sortation change time and thereby less parcels not sorted in the allocated wave.

Lastly, reviewing the dynamic lane allocation daily results in the best performance and fewer lane changes. Although it increases the complexity as more lane changes should be executed than with a static allocation and workers should learn a new topography every day. The higher performance is caused by the availability of actual order information. Due to the availability of actual order information on a daily planning horizon, it can be expected that a static lane allocation on a daily planning horizon may also result in a better performance. However, with a daily static lane allocation, workers should also learn the topography changes every day. Interestingly the number of lane changes decreases when determining the lane allocation on a daily basis. If a dynamic lane allocation is used for a long planning horizon (e.g. month), this makes it interesting to check at the start of the day whether all the changes between the waves are necessary and to eliminate the changes that do not bring any benefit. As a result, a more fixed and learnable schedule for the workers can be implemented with just a few minor changes during the day.

8. Conclusions and recommendations

In this chapter, the main conclusions, academic relevance, recommendations, limitations, and directions of further research are presented.

8.1. Conclusions

This study evaluated the main research question: *How does a dynamic carrier to sortation lane allocation, influence the performance of a manual picker-to-parts e-commerce warehouse, with a wave order release strategy?* Five sub-research questions were formulated to answer the main research question. Based on these sub-research questions the answer to the final research question is defined.

The first sub-research question investigated the possible solution designs for carrier-to-lane allocations: *What are suitable solution designs to allocate carriers to sortation lanes?* Depending on the layout of the warehouse and the characteristics of the carriers, the carrier-to-lane allocation can be solved in several ways. The carrier-to-lane allocation can be determined in long term, short term or partly on the long and short term. Furthermore, the allocation can be static during the day or can be more dynamic. A static long-term allocation is often used in warehouses in which the outgoing flows per carrier are steady and enough sortation lanes are available. When demand fluctuates more and the carriers have to compete for their place often a more short-term dynamic allocation is used.

The second sub-research question focused on measuring the performance of the carrier to sortation lane allocation and investigating the current sortation process of vidaXL. *How is the current sortation process of vidaXL designed and how does it perform?* Currently, vidaXL uses a fixed carrier-to-lane allocation, with limited changes between waves. The sortation system consists of internal and external sortation lanes, the handling costs of internal lanes are higher than those of external lanes. Handling costs are one of the most important performance measures of vidaXL. The overlap in the sortation of the waves makes it complex to change carriers from lanes between the waves. If waves do not overlap the picking efficiency will drop, which causes additional picking costs. Analysis shows that carrier volumes fluctuate. However, only updating the carrier-to-lane allocation more frequently and not allowing more lane changes between the waves, has only a limited effect on performance. Therefore, a dynamic allocation model, which allows for more lane changes, is being investigated.

The third sub-research question considered the translation of the problem to a suitable model design. *What kind of model can be developed to determine the carrier-to-lane allocation per wave, while minimizing the sortation handling costs?* It has been investigated how to allocate carriers more dynamically (allowing changes) to lanes and waves in a model, which takes into account the system constraints and minimizes the handling costs. From the literature study, it appears many methods are suitable to develop an allocation model, depending on the complexity of the situation. Although, the stochastic throughput time of orders in the warehouse, a mixed integer programming (MIP) approach was chosen, which ultimately resulted in mixed integer quadratic programming (MIQP). By setting constraints in the MIQP model based on the stochastic throughput time, it can be ensured that a minimum percentage of orders follow the allocation of the discrete model.

The fourth sub-research question dealt with the performance of the developed dynamic carrier-to-lane allocation model. *What are the effects on the warehouse performance for a more dynamic carrier to sortation lane allocation model?* The dynamic carrier-to-lane allocation model can determine a carrier-to-lane allocation that results in lower additional handling minutes compared to a static allocation model. However, with an overlap in the sortation of waves, the developed dynamic allocation will not perform better or even worse. Furthermore, due to the sortation lane changes, the model increases the complexity of the operation for the workers on the floor, since about 70% of the external lanes require a change between the waves.

The fifth research question focused on the planning horizon of the carrier-to-lane allocation: *What is the most cost-effective and user-friendly planning horizon of the carrier-to-lane allocation model to increase the performance of the sortation process?* The best planning horizon for the dynamic model, in terms of costs, will be a daily allocation or an updated allocation during the day. In terms of complexity, a daily or updated planning during the day reduces complexity by reducing the number of lane changes compared to a weekly or monthly planning horizon. However, the monthly planning horizon has less user complexity in terms of changes in lane allocation every day. Because the benefits of the daily allocation are not high and no clear difference can be seen in the actual performance, it can be concluded that a monthly allocation would be the best cost-effective and user-friendly trade-off. In addition, a daily review of the planned changes can reduce the number of changes and thereby the complexity of the operation.

In conclusion, the main research question can be answered. A dynamic carrier-to-lane allocation method in a warehouse with a wave order release strategy, can reduce the number of orders processed on an internal sortation lane and thereby reduce the handling costs, when no overlap in the sortation of waves exists or the overlap is minimized. When the overlap in the sortation of waves is too high a static wave allocation model performs better. Furthermore, a dynamic carrier-to-lane allocation increases the number of lane changes, which causes additional complexity. However, the number of changes can be reduced when the carrier-to-lane allocation is determined based on a daily planning horizon.

8.2. Academic relevance

From the literature study, it appeared that extensive research is done into the truck-to-dock allocation problem, mostly focusing on cross-dock warehouses, including parcel sortation centers, rather than traditional pick warehouses. Although the sortation process is sometimes comparable (conveyor system), the truck-to-dock allocation in cross-dock warehouses deals often with matching the inbound and outbound trucks, so that the time in stock in the cross-dock is minimized or the time loading the outbound truck is minimized. Furthermore, most research is carried out into the order-to-lane assignment policies for automatic sortation systems (bundling orders), however, less research is executed into the carrier-to-lane allocation for automatic sortation systems. In addition, there is no known research on sortation lanes with different characteristics on handling time and costs. This research contributes to this gap, by discussing a carrier-to-lane sortation system in a picker-to-part warehouse with a wave-based pick environment and different lane types. Moreover, this research contributes by developing a dynamic carrier-to-sortation lane allocation model that minimizes handling costs.

Lastly, research is done into warehouse wave order release policies, also in combination with automatic sortation systems. However, not much detailed research is carried out on wave release policies that allow overlapping waves. This research contributes to this gap by showing the effect of overlapping waves on the performance of the sortation operation. Moreover, this research contributes to the development of a simple heuristic that can determine the wave release and lane change time of a pick-wave in an environment with an overlap in the sortation of waves.

8.3. Limitations and future research

This section presents the limitations of the research and recommendations for future research.

First of all, the scope of the study is limited to the release of orders to the warehouse and the sortation of orders to a carrier. Therefore, it is assumed that orders that are released arrive at the sortation lanes according to a probability distribution. Incorporating the picking process in the modelling would probably result in a more accurate arrival of orders on the sortation lane. Furthermore, it would make it possible to determine the optimal second wave release time for picking or a combined optimum for sortation and picking. In the current design, the second wave release time is only based on the sortation process, while to reduce picking costs, the second wave often starts when the first picker is idle. This limitation creates an opportunity to investigate in the future the pick wave release time and to investigate the tradeoff between the optimal wave release time for both sortation and picking.

Furthermore, due to the scope of the research no alternative methods of working were considered to reduce the warehouse handling costs and/or reduce the overlap in the sortation of waves. For future research it would be interesting to investigate other methods. Firstly, (partly)dynamic teams, rather than separate picking and sortation teams. This will allow workers to switch between warehouse areas, which can also increases the job diversity of the warehouse worker. For example, a worker who completed all his pick tasks in a wave can join the sortation team, once sortation is finished, the worker can start picking the new wave. Secondly, workload balancing between pick zones during a wave can potentially contribute to a lower sortation overlap of the waves (Vanheusden et al., 2022). Also, buffering of orders before the sortation system can potentially reduce the overlap of the sortation in waves (Gallien & Weber, 2010).

Thirdly, in this research, a dynamic allocation model is developed and compared to a static allocation model. However, literature also suggests a semi-dynamic allocation model: a set of carriers is always allocated to a fixed lane while the other part can be switched dynamically (Fedtke & Boysen, 2017). Further research could investigate the influence of this on performance. However, the effect on the handling costs will probably be limited as carriers with a consistently high volume will almost always be allocated to an external lane by the dynamic model.

Fourthly, the wave sortation change time and wave release time are set to a fixed time for a single and double shift in the case study. Results could have been improved if the wave sortation change and the wave release time would have been based on the number of orders. The sortation change could then have been scheduled at the best time. This could be possible by slightly adjusting the system capacity heuristic and including it as a daily decision in the solution design. However, for simplification, it was chosen to set a fixed time, as this also seemed to be most realistic for the operation. Secondly, the solution design could have been extended by including a feedback loop from the simulation model and/or heuristic to the dynamic allocation model. Such the dynamic allocation model could anticipate on the actual performance by for example, varying the working schedules of the different teams, the number of waves, the wave capacity, the wave release times and wave sortation change times. Future research could investigate the potential performance benefits when the research design is extended.

Also, it was decided to only use data from the first wave to model the throughput time of order in all waves, because the coefficient of variation in the second wave increases as the number of orders increases. This results in two limitations for this research. Firstly, the throughput time of orders in the second wave does not take into account the fact that not all pick capacity is available at the release of the second wave, as still some pickers are finishing the first wave. Therefore, the arrival of orders in the second wave will be higher than expected in the first part of the distribution. Secondly, at the start of the day (during the first wave), the sortation workers start one hour later than the order pickers. Therefore, in the first hour no orders are sorted and some orders are buffered at the sortation system. While during the second wave, also orders can arrive at the sortation lane during the first hour. This is not taken into account in the throughput time distribution of the second wave and will result in a lower arrival pattern than expected in the first hour of the second wave and a slightly higher than expected arrival in the second hour of the wave. This limitation in modelling the throughput time may cause some inaccuracy in the computation of the system capacity and simulation. For future research, it may be interesting to discover why the coefficient of variation of the second wave increases with higher workloads.

Fifthly, all orders that arrive during the day, before the release of the second wave, are allocated to the second wave. This causes a lot of small volumes that will end up on an internal sortation lane, which reduces performance. In a real situation, not all these small volumes will always be released to the pickers, but they will be released the next day. Furthermore, in the case study, it is assumed every carrier has a departure every day, however, a few small-volume carriers will not depart every day. This will result in a higher percentage of orders to the internal sortation lane than expected, however as is the case in all scenarios, still a solid conclusion can be drawn between the scenarios.

Sixthly, it is assumed that all order arrivals are known in the case study scenarios that examine the performance of the dynamic carrier-to-lane allocation. If a forecast would have been used, for orders that are not yet arrived, the allocation of both the static and dynamic allocation models might differ a bit. However, because most of the order information is known at the start of the day, no major differences in model performance outcomes are expected.

Moreover, the forecasts used for investigating the planning horizon are made by vidaXL. When another period would have been selected the results may differ as the forecast may be less or more accurate. Furthermore, if the forecasting method were to be improved, it could also lead to other results and recommendations regarding the planning horizon.

Lastly, the additional handling time for 1 m^3 on the internal sortation lane is modeled based on plan norms and estimates of operational managers. A detailed time study on the additional handling time could provide a more accurate measure. Moreover, the reported potential savings in handling time do not necessarily translate into the same amount of working hours that can be saved. As it does not take into account fluctuations in the sortation volume during the day and a minimum worker occupation of the sortation area.

8.4. Managerial recommendations

Based on this research several recommendations for vidaXL can be formulated.

Firstly, implementing a dynamic carrier-to-lane allocation does not improve the sortation performance when the sortation of waves keeps overlapping. Furthermore, if waves do not overlap, the savings in terms of handling time are relatively low, while the number of lane changes is relatively high. It is therefore doubtful whether the additional complexity and potential investments to tackle the complexity outweigh the savings of implementing a dynamic carrier-to-lane allocation.

Although, it is not recommended to implement the dynamic carrier-to-lane allocation in the current situation and in the new outbound warehouse with more external sortation lanes. Nevertheless, still some recommendations can be made:

- Ensure the overlap between the sortation of the waves is as low as possible. Otherwise, the few lane changes that are executed have no or little benefit. Some practical ideas can be implemented or investigated to reduce the overlap: label all pick containers with the wave number, buffer orders by starting the pick operation earlier, and schedule the breaks of pickers and sortation workers around the first pick wave end and first sortation wave end.
- Determine at the start of each day, with the use of the available order information, whether a planned carrier to change lanes is beneficial. This can reduce the number of changes during the day. Only execute changes with a benefit above a minimum volume.
- To determine the moment of wave release and wave change use the expected throughput time of the orders. In a same way as the heuristic determines the system boundaries in this study. This will result in a better moment of sortation change between waves.
- Examine the throughput time distribution with data of the new outbound warehouse, to see if it behaves differently. With the introduction of the new warehouse, fewer cross docks between warehouses need to be executed and more orders are directly loaded on the sortation system. Another throughput time distribution can affect results, wave overlap, and the system capacity heuristic.
- From the orders that arrive after the release of the first wave, only consider releasing the orders that are allocated to an external lane and the higher volumes. Releasing all orders in the second wave would cause many small volumes for carriers of which most orders are released in the first wave and result in a higher number of orders through the internal sortation lane.
- Investigate the performance of the forecasts and investigate whether it is possible to accurately forecast the daily differences in a week between the carriers. An accurate forecast for each day can result in an allocation different for each weekday, but fixed for a long period of time.

When the number of carriers increases in the new outbound warehouse and the sortation of waves can be separated, it may eventually become interesting to implement a dynamic carrier-to-lane allocation. When implementing a dynamic carrier-to-lane allocation some additional recommendations can be made:

- Review the carrier-to-lane allocation daily or even before each wave release. A daily planning horizon reduces the handling time and furthermore, reduces the number of lane changes between waves.
- Reduce the early carrier departures, which will result in more orders with a due date after the last wave. Therefore, more orders are allowed in both waves, which gives the dynamic allocation model more freedom in allocating orders to waves. Which will result in a better carrier-to-lane allocation.

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Appendices

Appendix 1: Throughput time analysis

A.1.1. Throughput time analysis single and double shift

Double shift

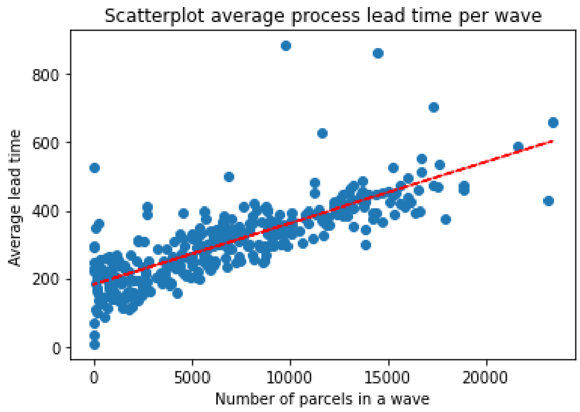


Figure 52: Average throughput time and number of parcels in double shift period

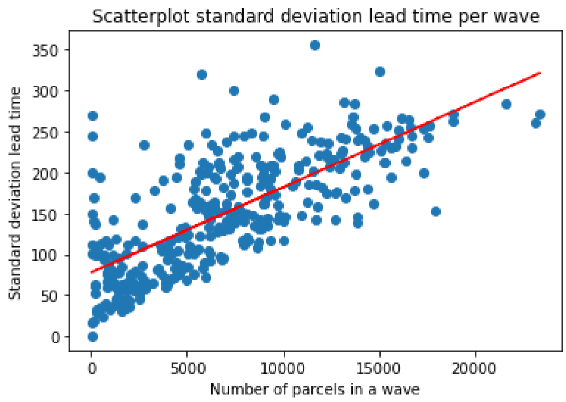


Figure 51: Standard deviation average throughput time and number of parcels in double shift period

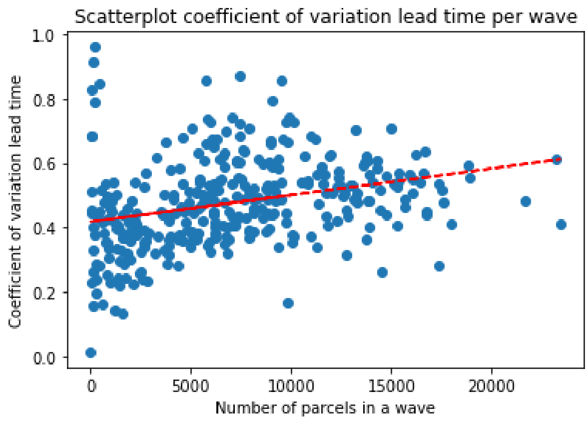


Figure 53: Coefficient of variation average throughput time and number of parcels in single shift period

Average throughput time: A positive correlation *($r(362) = 0.79$, $p < 0.01$)* between the average throughput time and the number of parcels. The trend line for the average throughput time is equal to 0.01788**number of parcels + 183.10.*

Average throughput time standard deviation: A positive correlation *($r(362) = 0.74$, $p < 0.01$)* between the average throughput time *standard deviation* and the number of parcels. The trend line for the average throughput time *standard deviation* is equal to 0.010399**number of parcels* + 77.77.

Average throughput time coefficient of variation: A positive correlation *($r(362) = 0.30$, $p < 0.01$)* between the average throughput time *coefficient of variation* and the number of parcels. The trend line for the average throughput time *coefficient of variation* is equal to 0.0000083**number of parcels + 0.42.*

Double and single shift

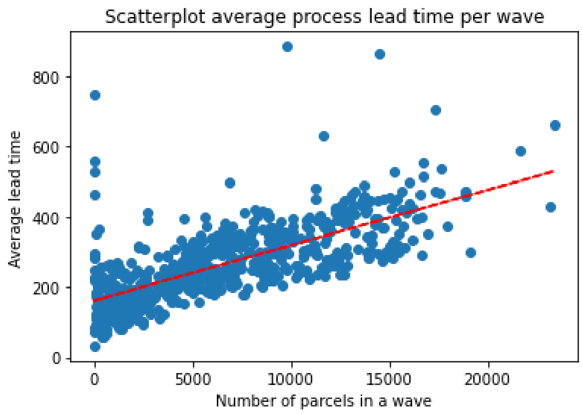


Figure 55: Average throughput time and number of parcels in both periods

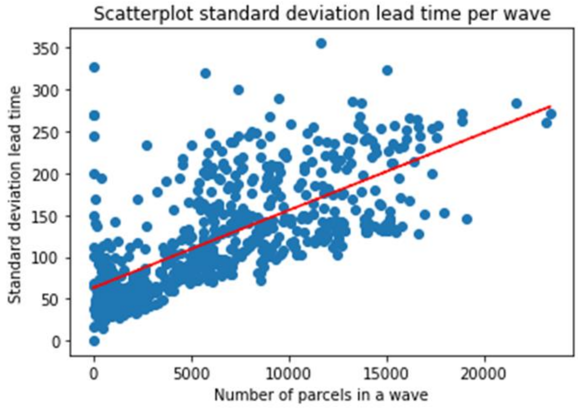


Figure 54: Standard deviation average throughput time and number of parcels in both periods

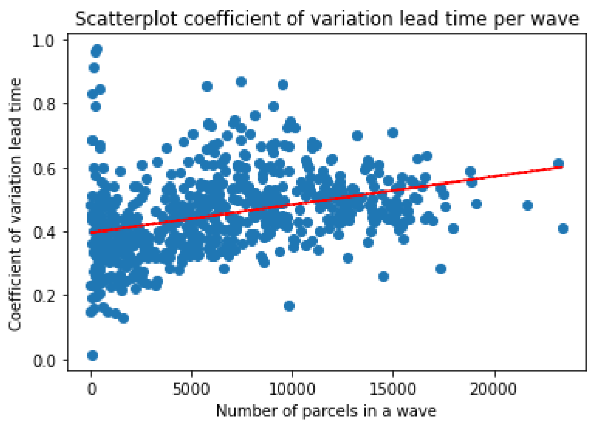


Figure 56: Coefficient of variation average throughput time and number of parcels in both periods

Average throughput time: A positive correlation *(r(654) = 0.71, p < 0.01)* between the average throughput time and the number of parcels. The trend line for the average throughput time is equal to 0.01575**number of parcels* + 160.84*.*

Average throughput time standard deviation: A positive correlation *(r(654) =* 0.69*, p < 0.01)* between the average throughput time *standard deviation* and the number of parcels. The trend line for the average throughput time *standard deviation* is equal to 0.09267**number of parcels* + 62.84*.*

Average throughput time coefficient of variation: A positive correlation *(r(654) = 0.34, p < 0.01)* between the average throughput time *coefficient of variation* and the number of parcels. The trend line for the average throughput time *coefficient of variation* is equal to 0.0000088**number of parcels + 0.39.*

A.1.2. Additional throughput time analysis of wave 1 and 2

In this analysis the throughput time is corrected for the breaks of the workers in the warehouse, 2 working days with divergent working times are removed and only standard orders (non-packing) are considered.

Wave 1&2

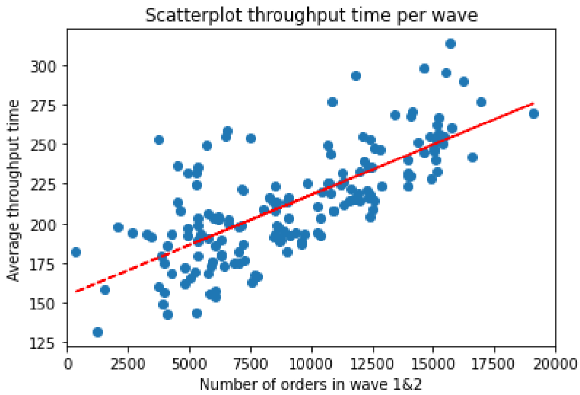


Figure 58: Average throughput time and number of orders in wave 1 and 2

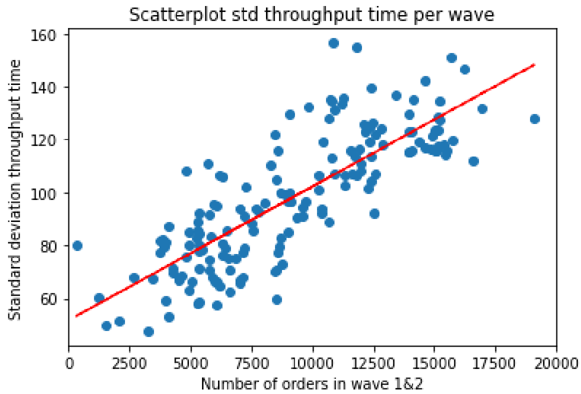


Figure 57: Standard deviation average throughput time and number of parcels in wave 1&2

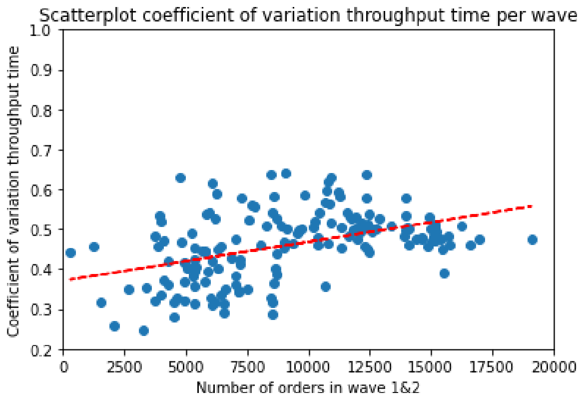


Figure 59: Coefficient of variation average throughput time and number of parcels in wave 1&2

Average throughput time: A positive correlation *($r(162) = 0.73$, $p < 0.0001$)* between the average throughput time and the number of parcels. The trend line for the average throughput time is equal to 0.00633**number of parcels* + 154.56 ($R^2 = 0.53$).

Average throughput time standard deviation: A positive correlation *($r(162)$* = 0.80, *$p < 0.0001$)* between the average throughput time *standard deviation* and the number of parcels. The trend line for the average throughput time *standard deviation* is equal to 0.00504**number of parcels* + 51.73 ($R^2 = 0.65$).

Average throughput time coefficient of variation: A positive correlation *($r(162) = 0.45$, $p < 0.0001$)* between the average throughput time *coefficient of variation* and the number of parcels. The trend line for the average throughput time *coefficient of variation* is equal to 0.0000009**number of parcels + 0.37* ($R^2 = 0.20$).

Wave 1

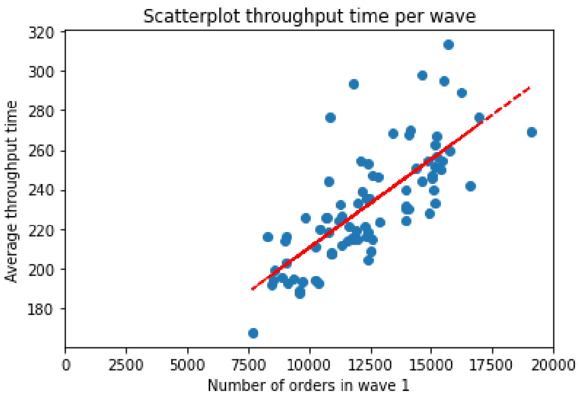


Figure 61: Average throughput time and number of orders in wave 1

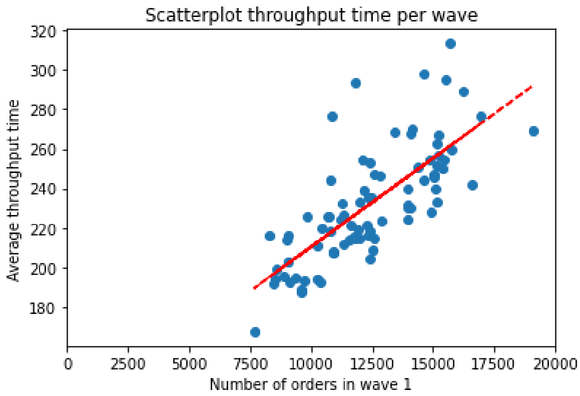


Figure 60: Standard deviation average throughput time and number of parcels in wave 1

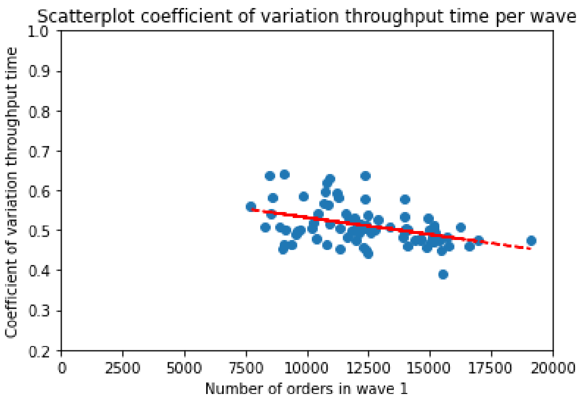


Figure 62: Coefficient of variation average throughput time and number of parcels in wave 1

Average throughput time: A positive correlation *($r(80) = 0.75$, $p < 0.0001$)* between the average throughput time and the number of parcels. The trend line for the average throughput time is equal to 0.00897**number of parcels* + 120.69 ($R^2 = 0.56$).

Average throughput time standard deviation: A positive correlation *($r(80) = 0.41$, $p = 0.0001$)* between the average throughput time *standard deviation* and the number of parcels. The trend line for the average throughput time *standard deviation* is equal to 0.00252**number of parcels* + 86.81 ($R^2 = 0.17$).

Average throughput time coefficient of variation: A negative correlation *($r(80) = -0.42$, $p < 0.0001$)* between the average throughput time *coefficient of variation* and the number of parcels. The trend line for the average throughput time *coefficient of variation* is equal to -0.0000009**number of parcels + 0.62* ($R^2 = 0.18$).

Wave 2

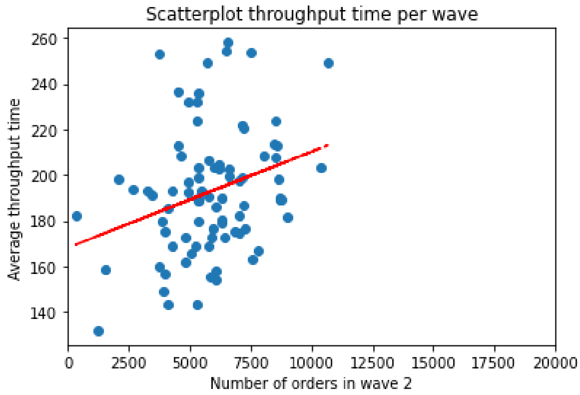


Figure 64: Average throughput time and number of orders in wave 2

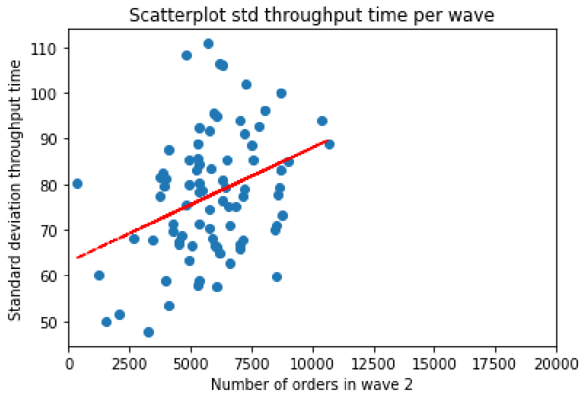


Figure 63: Standard deviation average throughput time and number of parcels in wave 2

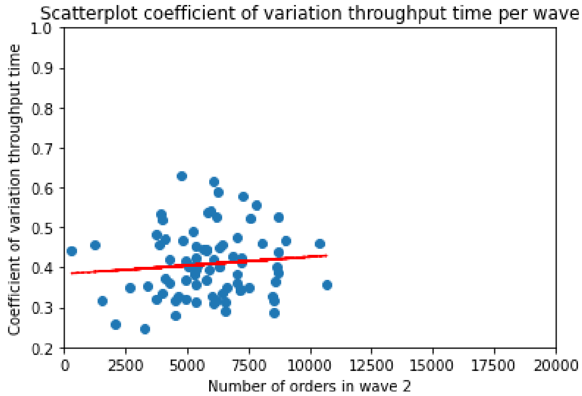


Figure 65: Coefficient of variation average throughput time and number of parcels in wave 2

Average throughput time: A positive correlation *(r(80) = 0.29, p = 0.007)* between the average throughput time and the number of parcels. The trend line for the average throughput time is equal to 0.00421**number of parcels* + 168.10 (R^2 = 0.09).

Average throughput time standard deviation: A positive correlation *(r(80)* = 0.41*, p = 0.001)* between the average throughput time *standard deviation* and the number of parcels. The trend line for the average throughput time *standard deviation* is equal to 0.002502**number of parcels +* 62.95 (R^2 = 0.12).

Average throughput time coefficient of variation: No significant correlation *(r(80) = 0.10, p =0.37)* between the average throughput time *coefficient of variation* and the number of parcels. The trend line for the average throughput time *coefficient of variation* is equal to 0.0000004**number of parcels + 0.38* (R^2 = 0.01).

A.1.3. Workload in the pick area

vidaXL has a plan norm of one additional work hour for 80 picks. To check that the throughput time is not affected by adding fewer working hours than the defined norm to the system, a small analysis is carried out.

Picks per hour on a day

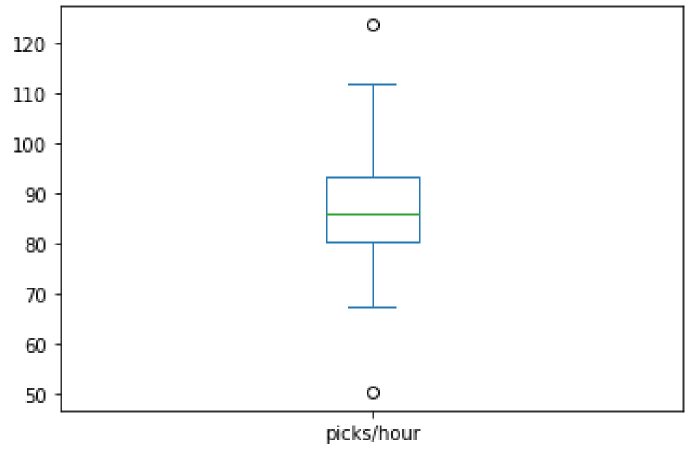


Figure 66: boxplot picks per hour

The mean of the average picks per hour on a day is 86.98 with a standard deviation of 11.41. Showing that on average the picks per hour are in line with the norm.

Number of picks and working hours

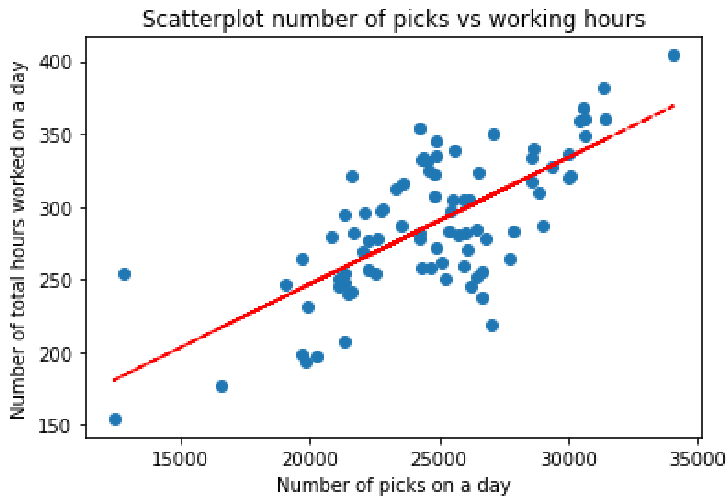


Figure 67: Scatterplot number of picks and total hours worked on a day

Trendline: y = 0.008695x + 72.823818

Figure 67 shows the number of picks on a day and the number of picking working hours ($r(80)$ = 0.71, $p < 0.001$). According to the trendline (y = 0.008695 number of picks + 72.82), for 115 picks one additional hour of work is added. So, the number of hours worked compared to the number of picks on a day, does not increase according to the plan norm of 80 picks per hour. However, the intercept is 73 hours, which ensures that during a busy day the average picks per hour is still reasonable compared to the norm. Furthermore, it is reasonable the number of picks per picker can increase a bit as the number of picks increases as the efficiency of the picking process will increase.

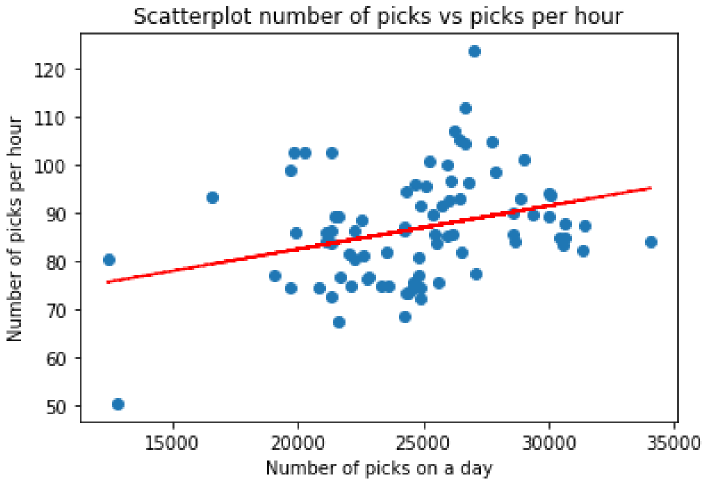


Figure 68: Scatterplot number of picks and number of picks per hour

Appendix 2: internal versus external lane

A.2.1. Overview

Table 11: Number of parcels per lane per day

	Single shift (8h)		**Double shift (16h)**	
Number of parcels per lane per day	*Internal chute*	*External chute*	*Internal chute*	*External chute*
mean	205.41	855.46	348.86	1.049.47
std	244.59	406.57	329.06	479.48
min	1	132	4	161
max	1405	2665	2.699	3.908
max mean per work hour	175.63	333.13	168.69	244.25
Number of lanes	19	18	19	18

A.2.2. Boxplot number of parcels per internal and external lane per day

Double shift

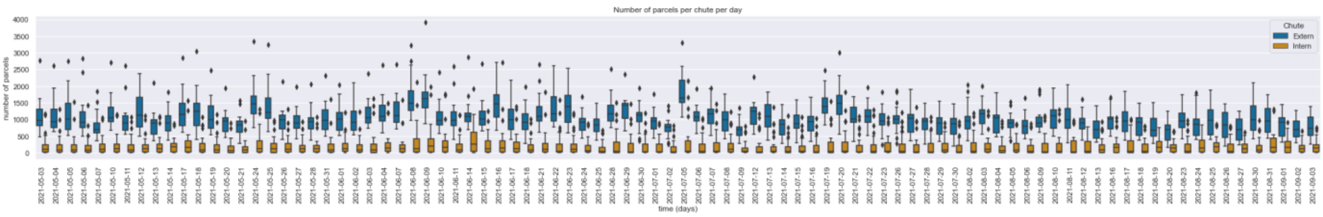


Figure 69: Boxplot number of parcels per internal and external lane per day during a double shift

Single shift

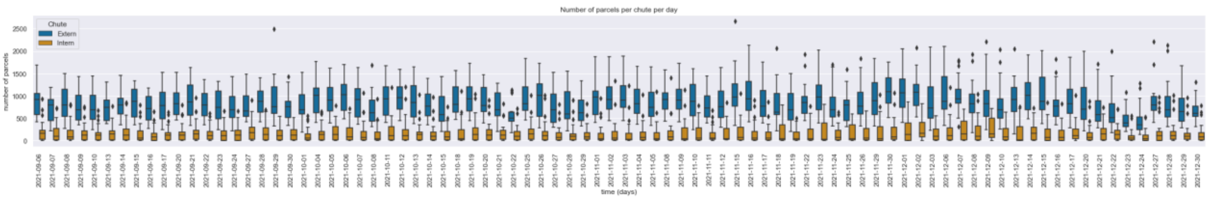


Figure 70: Boxplot number of parcels per internal and external lane per day during a single shift

A.2.3. Number of parcels versus percentual usage of internal lane

Double shift

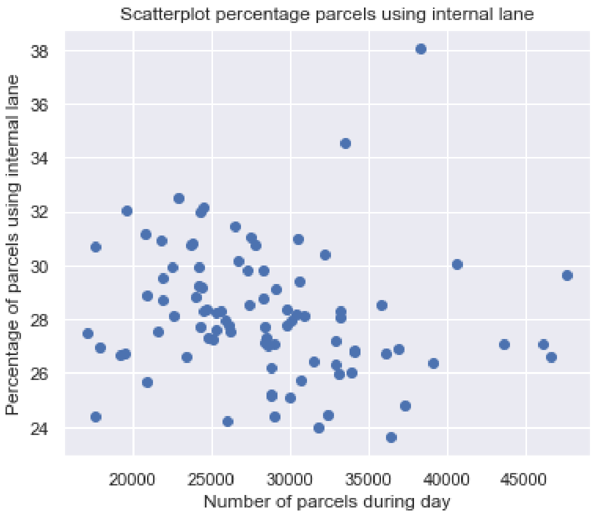


Figure 71: Scatterplot percentage parcels via internal lane versus the number of parcels during double shift

There seems to be no correlation between the number of parcels and the usage of the internal chute when looking at double shift data *(r(88) = -0.13, p = 0.22)*.

Single shift

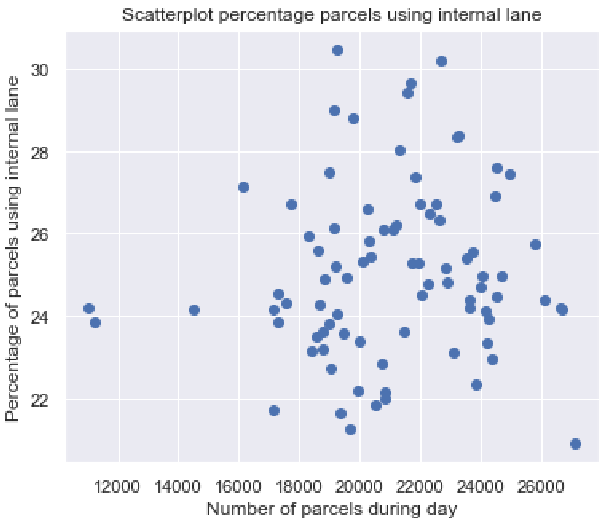


Figure 72: Scatterplot percentage parcels via internal lane versus the number of parcels during a single shift

There seems to be no correlation between the number of parcels and the usage of the internal chute when looking at double shift data *(r(82) = 0.08, p = 0.48)*.

Single and double shift

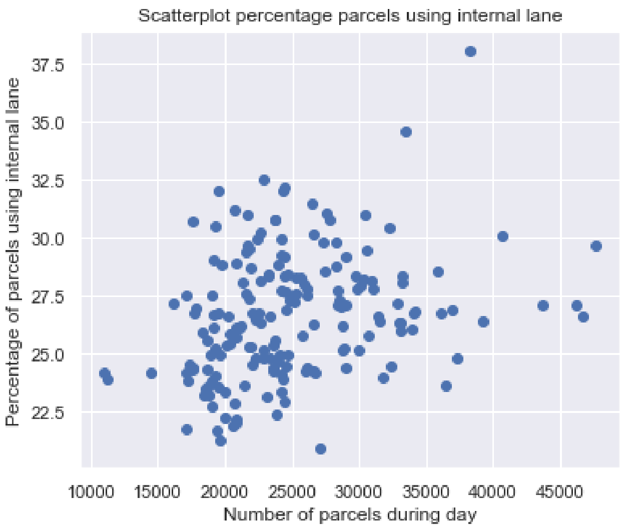


Figure 73: Scatterplot percentage parcels via internal lane versus the number of parcels during single and double shift

There is a low correlation between the number of parcels and the usage of the internal chute when looking at the double and single shift data *(r(177) = 0.29, p <0.01)*.

Appendix 3: parcels per carrier

Double shift

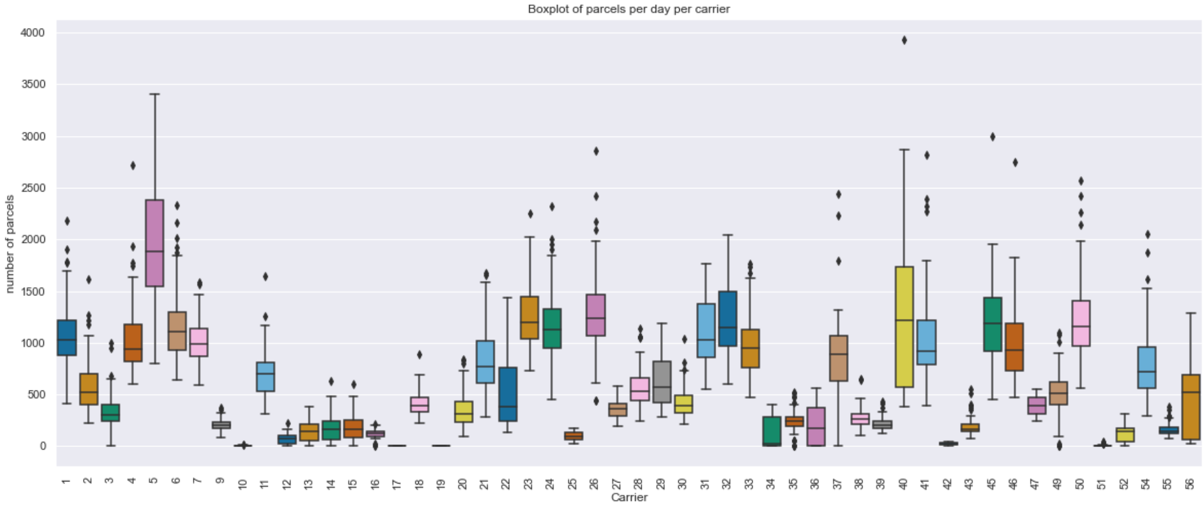


Figure 74: Boxplot of number of parcels per carrier per day during a double shift

Single shift

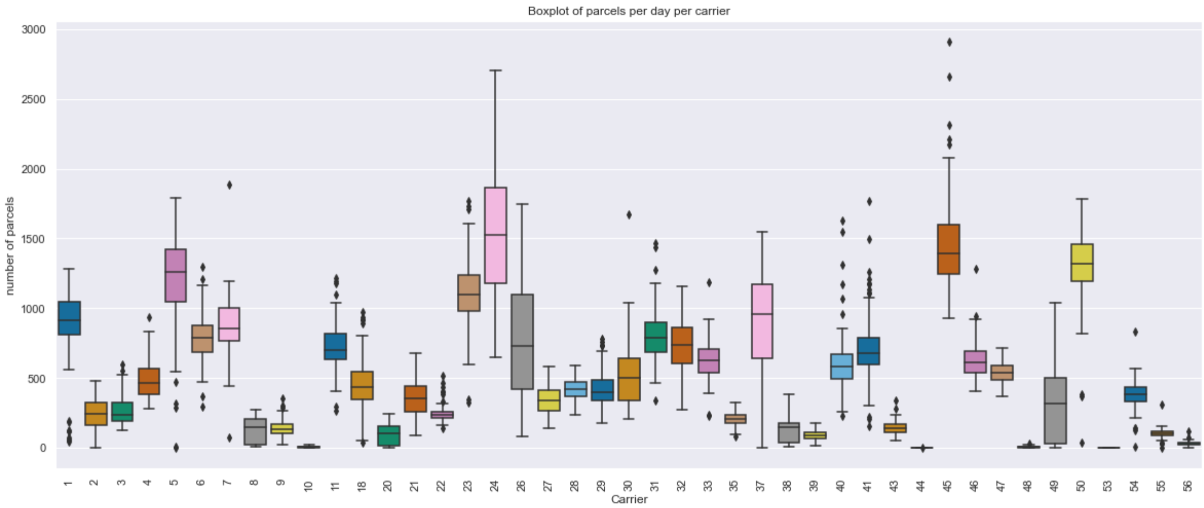


Figure 75: Boxplot of number of parcels per carrier per day during a single shift

Appendix 4: throughput time distribution

A.4.1. Linear regression model mean throughput time and number of orders

A high positive correlation exists between the number of non-packing orders in wave 1 and the mean of the throughput time (r(80) = 0.75, p < 0.0001). Based on this a linear regression model is developed with the use of R-studio. Resulting in the equation $\mu_t = 0.008970\ \text{numberofnonpackingorders} + 60.69$. The adjusted R^2 is 0.55, which indicates that this model predicts 55% of the variance in mean throughput time. In the scatterplot of the residuals no structure exists and thus the assumption of heteroscedasticity is met.

Model summary:

```
Residual standard error: 19.46 on 80 degrees of freedom
Multiple R-squared:  0.5583,   Adjusted R-squared:  0.5527
F-statistic: 101.1 on 1 and 80 DF,  p-value: 7.551e-16
```

Coefficients:

```
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 6.069e+01  1.129e+01   5.378 7.28e-07 ***
size_sort   8.970e-03  8.921e-04  10.055 7.55e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Residuals:

```
    Min      1Q  Median      3Q     Max
-27.582 -13.065  -4.308   9.274  66.952
```

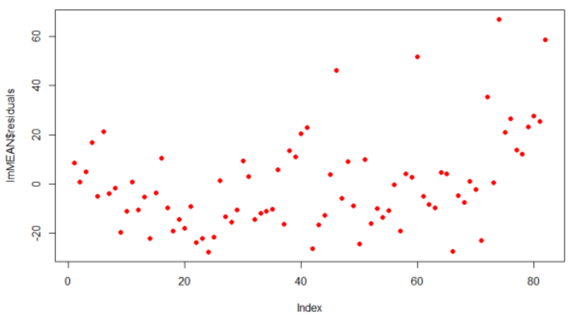


Figure 77: Residuals of the throughput time mean regression model

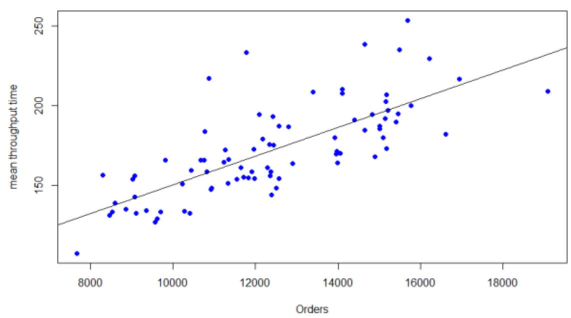


Figure 76: Line equation of throughput time mean regression model

A.4.2. Power law mean and standard deviation throughput time

A positive correlation exists between the mean and standard deviation of the throughput time of wave 1 (r(80) = 0.71, p < 0.0001). A negative correlation exists between the number of non-packing orders in wave 1 and the coefficient of variation of the throughput time (r(80) = -0.42, p < 0.0001). Which indicates that when μ_t increases σ_t will increase but relatively less. Therefore no linear relationship between μ_t and σ_t exists and it is chosen to fit a power law, with the use of linear regression. First a linear regression model is developed based on the $ln(\sigma_t)$ and the $ln(\mu_t)$. Resulting in $ln(\sigma_t) = 0.8328 + 0.7227 ln(\mu_t)$. The adjusted R^2 is 0.51, which indicates that this model predicts 51% of the variance in $ln(\sigma_t)$. In the scatterplot of the residuals no structure exists and thus the assumption of heteroscedasticity is met. The regression equitation is transformed to a power law with $\sigma_w = 2.29975 \mu_w^{0.7227}$.

Model summary:
```
Residual standard error: 0.0886 on 80 degrees of freedom
Multiple R-squared:  0.5081, Adjusted R-squared:  0.5019
F-statistic: 82.62 on 1 and 80 DF,  p-value: 5.856e-14
```

Coefficients:
```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.8328     0.4326   1.925   0.0577 .
lnMean        0.7227     0.0795   9.090 5.86e-14 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Residuals:
```
     Min       1Q   Median       3Q      Max
-0.19175 -0.05987 -0.01256  0.04255  0.21092
```

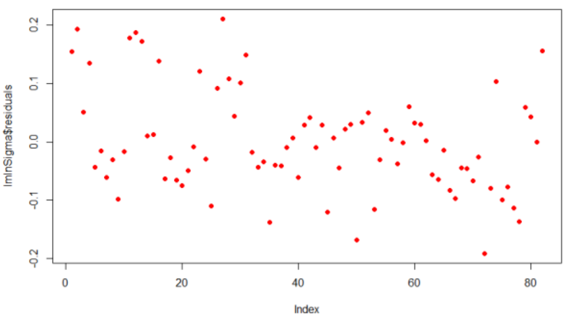


Figure 79: Residuals of the ln(std) regression model

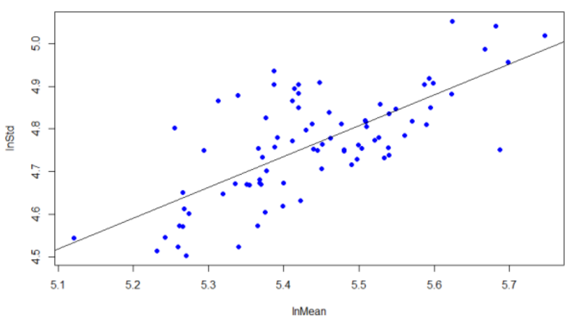


Figure 78: Line equation of ln(std) regression model

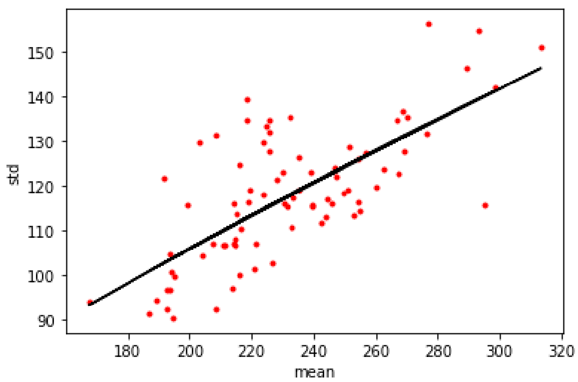
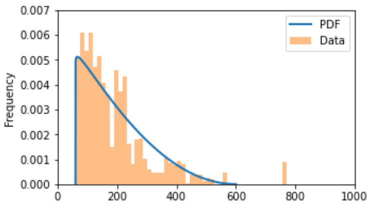
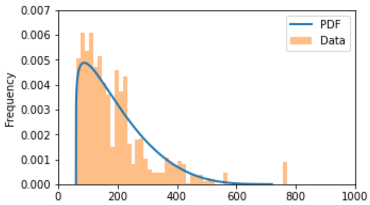
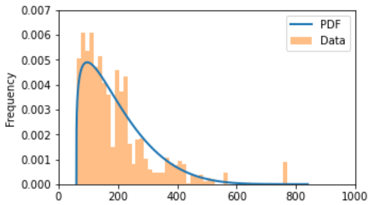
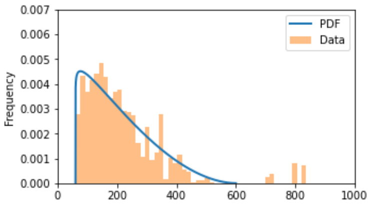
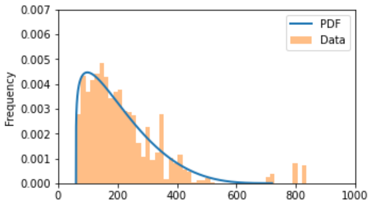
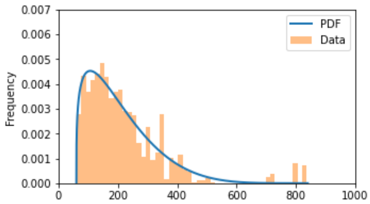
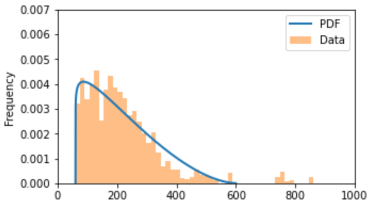
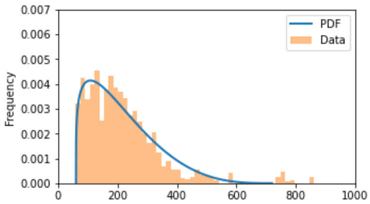
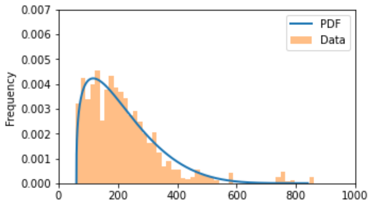
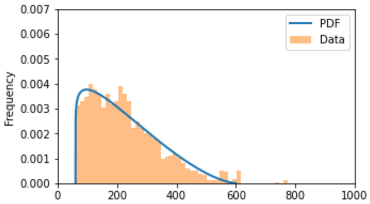
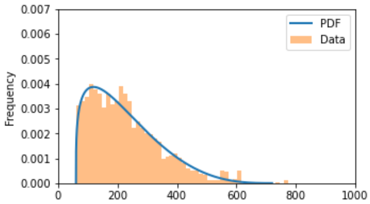
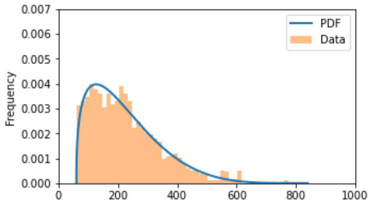
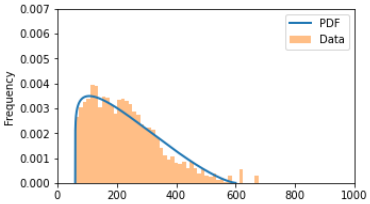
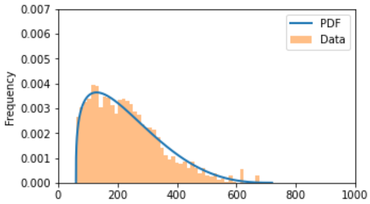
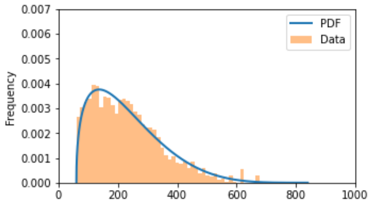
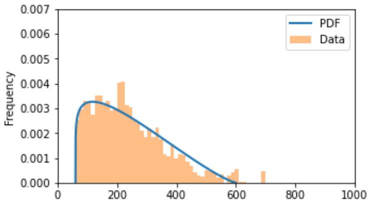
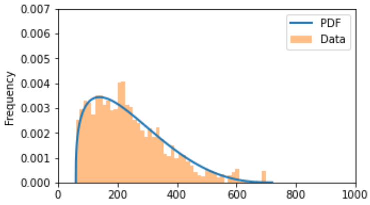
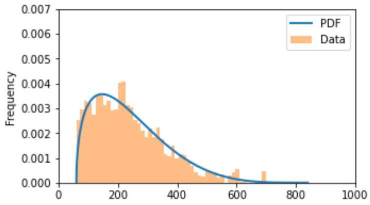


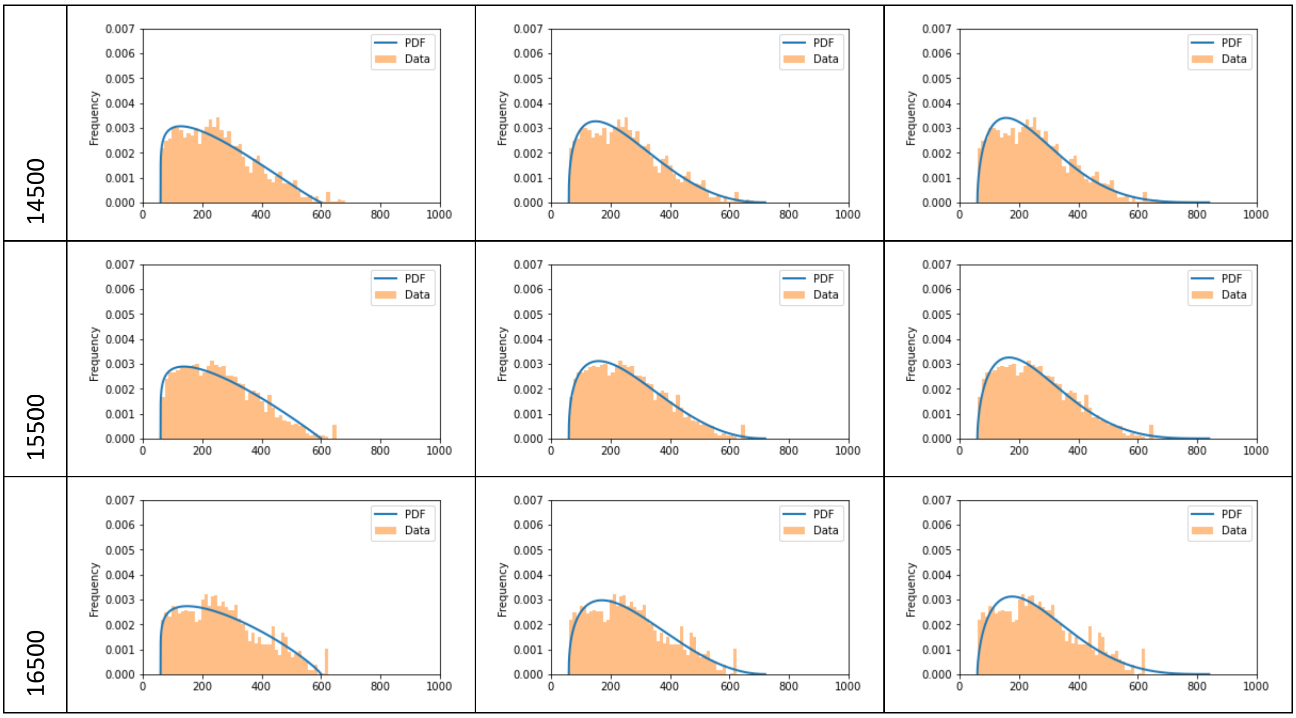
Figure 80: Power law model

A.4.3. Check fit of beta throughput time distribution

Table 12 below shows the fit of the beta distribution towards historic data. The beta distribution parameters are determined based mean and variation of the number of orders (indicated on the left side). The data visualized is selected by taking historic waves with plus and minus 500 orders of the number of orders used for the distribution. The result shows the beta distribution fit is reasonable. Furthermore c is determined by looking to the fit of the tail of the distribution, a few examples (e.g. c 600, 720 and 840) are shown below. Eventually c = 720 is selected.

Table 12: Fit of beta distribution

	$\boldsymbol{Beta(\alpha, \beta, a = 60, c = 600)}$	$\boldsymbol{Beta(\alpha, \beta, a = 60, c = 720)}$	$\boldsymbol{Beta(\alpha, \beta, a = 60, c = 840)}$
8500			
9500			
10500			
11500			
12500			
13500			



A.4.4. Check fit of beta pack order throughput time distribution

Below the beta distribution ($\mathrm{Beta}(\alpha = 3.5335, \beta = 10.4377, a = 60, c = 1140)$) of the throughput time of pack orders ($\mu = 333.1489,\ \sigma = 1213298$) is visualized with the packed orders.

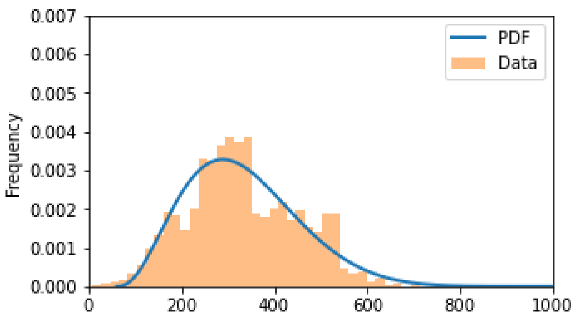


Figure 81: Beta pack order throughput time distribution

Appendix 5: Cost comparison internal and external lane

This appendix shows the computation of the additional handling costs of an internal lane compared to an external lane. To do so first all processes are distinguished and average handling time per order per process is determined (Table 13). The handling time of the processes cannot be determined by data analysis. Therefore, the handling time is determined based on the norm, some observations and discussions with the operations manager and supply chain manager. Because the times can variate and no good measures are available a high and low costs scenario is computed. Both scenarios are face validated with a business analyst responsible for analysis about the warehouse workers and with the supply chain manager. In the future a detailed analysis of the time per process should be executed to determine the exact costs. However, as the costs parameter is only a fixed parameter in the model it will not have an influence on the performance of the model defined in this research.

Table 13: Processes and time indication of internal and external lane in a lower and upper bound scenario

Process	**Lane type**	**High cost scenario**		**Low cost scenario**	
		Norm/observations	*Time per order*	*Norm/observations*	*Time per order*
Grab + Scan + place in container	Internal	100 orders per hour per worker	36/sec 0.6/min	150 orders per hour per worker	24/sec 0.4/min
Move container to dock	internal	180 seconds per container 25 parcels in a roll container	7.2/sec 0.12/min	120 seconds per container 25 parcels in a roll container	4.8/sec 0.08/min
Place order on belt	Internal	5 seconds per order	5/s 0.08/min	3 seconds per order	3/sec 0.05/min
Grab + place in trailer	internal & external	350 orders per hour per 2 workers	20.6/sec 0.34/min	350 orders per hour per 2 workers	20.6/sec 0.34/min
Total			68.8/sec 1.15/min		52.4/sec 0.87/min

An order send has a standard volume of 0.06 m^3. This means on average 16.67 orders will fit in 1 m^3. Table 14, shows an indication of the additional handling time of an internal lane. The handling cost are left out of this report due to confidential reasons, however, the additional handling time is reported.

Table 14: Indication of the handling time difference between internal and external lane

	High costs scenario	**Low costs scenario**
Additional time internal lane per order	48.2/sec 0.80/min	31.8/sec 0.53/min
Additional internal lane time per m^3	13.34 min	8.84/min

Appendix 6: MILP order to wave allocation

The MILP model described below is a sub-model of the MIQP model discussed in chapter 5. The same parameters and variables are used. The model can be used to allocate orders to an wave when carrier to wave to lane allocation is known ($X_{w,c,l}$ is given). This means that $Y_{w,o}$ is the only decision variable.

Objective function

$$\min \sum_{w \in W} \sum_{c \in C} \sum_{l \in L} \sum_{o \in O} C^I (1 - A_l) X_{w,c,l} V_o B_{c,o} Y_{w,o} + \sum_{w \in W} \sum_{o \in O} PW_{w,o} Y_{w,o} \qquad (1)$$

The objective (1) can be rewritten in (2):

$$\min \sum_{w \in W} \sum_{c \in C} \sum_{l \in L} \sum_{o \in O} C^I X_{w,c,l} V_o B_{c,o} Y_{w,o} - C^I A_l X_{w,c,l} V_o B_{c,o} Y_{w,o} + PW_{w,o} Y_{w,o} \qquad (2)$$

Constraints

The volume processed on a lane cannot be higher than the lane capacity during a wave

$$\sum_{o \in O} V_o B_{c,o} Y_{w,o} \leq CAPL_w \qquad \forall\, w \in W, c \in C \qquad (3)$$

The volume processed during a wave cannot be higher than the maximum wave capacity of the wave

$$\sum_{c \in C} \sum_{o \in O} V_o B_{c,o} Y_{w,o} \leq CAPW_w \qquad \forall\, w \in W \qquad (4)$$

All orders should be assigned before the defined due date

$$\sum_{w \in W} D_{w,o} Y_{w,o} = 1 \qquad \forall\, o \in O \qquad (5)$$

The following constraints ensure that the decision variable $Y_{w,o}$ is binary and can only take values 0 and 1.

$$Y_{w,o} \in \{0,1\} \qquad (6)$$

Appendix 7: System capacity

A.7.1. Single shift

In a single shift the division of orders between the waves is set to 60% in wave 1 and 40% in wave 2. The system capacity cannot be computed for waves lower than 6000, as the beta throughput time distribution is not valid for waves smaller than 6000 orders. Therefore, the computation can be only executed for a total number of orders higher than 15000.

Table 15: Single shift: Maximum number of planned orders on a day based on system capacity settings (table 10)

→: % of orders sorted in required wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders sorted at end of wave 2						
95%	N/A	N/A	N/A	15144	17477	19792
90%	N/A	N/A	16761	19524	22167	24934
85%	N/A	16199	19581	22554	25484	28595
80%	N/A	18301	21843	25022	28208	31605
75%	15193	20100	23802	27182	30600	34253
70%	16648	21712	25575	29151	32789	36680

Table 16: Single shift: Time in minutes of sortation change between wave 1 and 2 based on system capacity settings

→: % of orders sorted in required wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders sorted at end of wave 2						
95%	N/A	N/A	N/A	232	218	209
90%	N/A	N/A	277	262	252	251
85%	N/A	317	298	285	280	282
80%	N/A	334	316	305	303	308
75%	372	348	331	323	323	332
70%	385	361	346	340	342	353

Table 17: Single shift: Time in minutes of release of wave 2 based on system capacity settings

→: % of orders sorted in required wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders sorted at end of wave 2						
95%	N/A	N/A	N/A	172	158	145
90%	N/A	N/A	217	202	187	171
85%	N/A	257	238	222	206	190
80%	N/A	274	255	238	222	204
75%	312	288	269	253	236	218
70%	325	301	282	265	248	229

A.7.2. Double shift

In a single shift the division of orders between the waves is set to 50% in wave 1 and 50% in wave 2.

Table 18: Double shift: Maximum number of planned orders on a day based on system capacity settings (table 11)

→: % of orders sorted in required wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders sorted at end of wave 2						
95%	41873	49785	56377	62634	68953	75601
90%	47674	56403	63702	70631	77619	84950
85%	51792	61136	68967	76402	83894	91737
80%	55192	65067	73359	81234	89164	97454
75%	58202	68568	77287	85573	93913	102624
70%	60983	71820	80953	89637	98379	107509

Table 19: Double shift: Time in minutes of sortation change between wave 1 and 2 based on system capacity settings

→: % of orders sorted in required wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders sorted at end of wave 2						
95%	522	501	494	493	497	505
90%	564	546	543	545	552	565
85%	593	579	578	583	594	610
80%	617	606	608	616	629	650
75%	638	630	634	645	663	688
70%	658	653	660	674	695	726

Table 20: Double shift: Time in minutes of release of wave 2 based on system capacity settings

→: % of orders sorted in required wave	*95%*	*90%*	*85%*	*80%*	*75%*	*70%*
↓: % of orders sorted at end of wave 2						
95%	438	384	340	298	257	215
90%	471	414	368	323	279	234
85%	494	436	387	342	296	248
80%	513	454	404	357	309	259
75%	528	469	419	370	321	270
70%	544	483	432	383	333	280

Appendix 8: Forecast error

Appendix 8 shows the performance (MAE and RMSE) of the forecasts of the different planning and forecast horizons used in the case study. Appendix A.8.1. shows the forecast performance per carrier over the complete simulation period. Appendix A.8.2. shows the forecast performance per day over all carriers.

A.8.1. Forecast error per carrier

Table 21: Forecast performance per carrier per forecast period over simulated case study period

Forecast period →	**Month**		**Week**		**Day**	
Carrier↓	*MAE*	*RMSE*	*MAE*	*RMSE*	*MAE*	*RMSE*
1	15.53%	17.38%	13.35%	16.86%	8.30%	8.78%
2	25.65%	33.75%	26.57%	34.49%	16.07%	17.38%
3	26.09%	41.36%	27.47%	42.25%	6.54%	8.09%
4	23.37%	31.52%	23.43%	31.82%	1.91%	2.33%
5	23.51%	31.88%	24.40%	31.49%	0.91%	1.17%
6	12.60%	15.40%	13.88%	17.03%	1.92%	2.33%
7	18.13%	21.13%	15.19%	18.64%	2.07%	2.53%
8	12.83%	13.90%	14.30%	16.48%	8.62%	10.03%
9	38.71%	51.28%	36.78%	50.65%	2.50%	3.49%
10	53.58%	119.51%	52.40%	119.17%	7.50%	13.28%
11	43.69%	53.39%	43.11%	52.91%	7.39%	9.13%
12	34.50%	42.23%	35.37%	41.35%	7.03%	8.08%
13	34.85%	41.48%	36.52%	41.77%	6.89%	8.19%
14	102.93%	114.20%	106.11%	116.55%	7.11%	10.64%
15	23.79%	30.90%	25.11%	32.83%	3.48%	4.17%
16	40.51%	55.66%	38.74%	53.46%	9.50%	11.60%
17	17.21%	23.07%	17.73%	21.94%	7.81%	8.51%
18	24.07%	29.98%	22.57%	28.91%	5.45%	6.12%
19	14.49%	18.73%	16.45%	20.66%	1.29%	1.67%
20	25.13%	28.91%	26.87%	30.20%	7.38%	8.01%
21	19.40%	25.10%	19.39%	25.38%	2.26%	2.63%
22	29.91%	33.72%	31.84%	37.62%	2.80%	3.60%
23	36.63%	42.07%	38.68%	43.93%	11.20%	12.20%
24	13.32%	17.97%	12.36%	18.57%	3.50%	4.00%
25	16.59%	19.55%	16.31%	19.43%	5.14%	5.68%
26	9.56%	10.75%	7.56%	9.16%	1.30%	1.72%
27	9.96%	11.52%	9.86%	11.10%	1.26%	1.52%
28	14.73%	18.18%	16.64%	21.11%	5.13%	5.53%
29	65.38%	111.14%	65.16%	111.16%	5.78%	8.57%
30	27.70%	38.56%	27.93%	38.69%	56.52%	61.87%
31	34.63%	48.65%	34.94%	48.41%	2.09%	2.70%
32	19.24%	23.42%	19.14%	24.37%	3.52%	4.38%
33	19.74%	22.35%	18.60%	21.78%	4.89%	5.49%
34	28.85%	33.72%	28.99%	34.20%	2.99%	3.73%
35	16.72%	19.37%	18.85%	22.04%	5.25%	5.77%
36	24.45%	28.42%	25.57%	29.52%	6.05%	6.55%
37	21.62%	27.48%	21.23%	27.45%	5.74%	6.58%
38	22.15%	25.80%	20.18%	23.52%	5.67%	6.09%
39	14.09%	16.75%	12.96%	15.85%	5.99%	6.31%

A.8.2. Forecast error per day

Table 22: Forecast performance per forecast period per day in simulated case study period

Forecast period →	**Month**		**Week**		**Day**	
Day ↓	*MAE*	*RMSE*	*MAE*	*RMSE*	*MAE*	*RMSE*
1	21.54%	27.23%	21.79%	27.66%	5.76%	10.28%
2	16.90%	22.19%	16.91%	22.41%	6.31%	12.95%
3	17.82%	22.97%	18.07%	23.40%	6.44%	13.52%
4	21.32%	28.05%	21.94%	28.83%	6.51%	14.59%
5	25.68%	32.36%	25.98%	32.68%	5.00%	7.41%
6	19.58%	25.74%	19.14%	24.92%	6.92%	16.75%
7	19.94%	30.89%	19.15%	30.02%	5.59%	9.99%
8	18.55%	25.41%	17.96%	25.33%	6.51%	14.35%
9	19.35%	27.66%	18.69%	27.07%	6.51%	12.22%
10	21.88%	39.36%	22.74%	39.80%	4.94%	6.87%
11	20.12%	32.29%	20.70%	32.62%	6.07%	12.69%
12	21.64%	31.76%	17.87%	27.84%	0.00%	0.00%
13	18.41%	26.52%	19.64%	27.45%	6.73%	13.74%
14	17.77%	39.00%	18.85%	40.26%	5.92%	11.26%
15	15.95%	25.48%	17.41%	28.26%	4.15%	5.77%
16	21.11%	27.24%	20.33%	27.43%	5.87%	10.57%
17	16.42%	23.39%	16.75%	24.29%	6.30%	13.35%
18	19.41%	26.65%	21.93%	30.13%	7.06%	15.67%
19	21.78%	28.53%	23.21%	30.27%	6.93%	14.61%
20	23.91%	32.20%	25.59%	34.78%	4.91%	7.16%
21	20.99%	31.70%	20.27%	30.43%	6.28%	13.78%
22	24.66%	33.67%	23.58%	31.63%	7.09%	16.60%
23	22.10%	28.76%	20.74%	26.79%	6.66%	14.59%
24	26.34%	34.76%	25.03%	33.81%	6.94%	13.76%
25	26.15%	34.97%	23.44%	32.79%	6.64%	13.90%

Appendix 9: Results case study

Appendix 9 shows the results of the case study. The CI interval computed is based on equation 10 with a significance level (α) of 5%.

A.9.1. Results dynamic allocation model

Table 23: Number of sortation lane changes between waves

	Dynamic allocation		
	MIQP		
Scenario	*Mean*	*SD*	*CI +/-*
Low-15000	11.8894	0.8944	1.1106
Low-20000	12.1337	1.0198	1.2663
Low-25000	11.3751	1.4697	1.8249
Low-30000	12.6066	0.8000	0.9934
High-30000	12.0000	1.0954	1.3602
High-40000	12.4000	0.8000	0.9934
High-50000	13.8000	1.1662	1.4480
High-60000	15.6000	0.4899	0.6083

Table 24: Percentage of volume of orders sorted via internal sortation lane

	Dynamic allocation						**Static allocation**					
	MIQP			*Simulation*			*MILP*			*Simulation*		
Scenario	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*
Low-15000	0.0904	0.0109	0.0135	0.1843	0.0087	0.0109	0.2208	0.0042	0.0052	0.2224	0.0049	0.0060
Low-20000	0.1027	0.0153	0.0190	0.2185	0.0110	0.0136	0.2236	0.0026	0.0032	0.2298	0.0042	0.0052
Low-25000	0.1232	0.0172	0.0213	0.2622	0.0085	0.0105	0.2216	0.0029	0.0036	0.2347	0.0050	0.0063
Low-30000	0.1542	0.0095	0.0118	0.2815	0.0207	0.0258	0.2233	0.0043	0.0053	0.2417	0.0052	0.0065
High-30000	0.2136	0.0201	0.0249	0.2739	0.0135	0.0167	0.2508	0.0015	0.0019	0.2596	0.0023	0.0028
High-40000	0.1905	0.0127	0.0158	0.2492	0.0099	0.0123	0.2493	0.0030	0.0038	0.2601	0.0033	0.0041
High-50000	0.1974	0.0083	0.0103	0.2602	0.0075	0.0094	0.2493	0.0014	0.0018	0.2638	0.0017	0.0021
High-60000	0.2189	0.0071	0.0088	0.2919	0.0079	0.0098	0.2504	0.0022	0.0027	0.2693	0.0020	0.0025

Table 25: Additional minutes spent on internal sortation lane

	Dynamic allocation						**Static allocation**					
	MIQP			*Simulation*			*MILP*			*Simulation*		
Scenario	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*
Low-15000	1150.46	140.55	174.52	2242.50	107.80	133.86	2810.48	58.78	72.99	2708.78	57.51	71.41
Low-20000	1740.10	254.96	316.58	3471.24	185.00	229.72	3791.18	46.24	57.41	3656.89	79.12	98.25
Low-25000	2623.17	364.69	452.83	5082.31	175.11	217.43	4718.48	55.25	68.60	4548.23	104.20	129.38
Low-30000	3924.92	244.15	303.16	6272.23	463.17	575.12	5681.46	106.00	131.62	5410.38	119.18	147.98
High-30000	5945.46	586.63	728.41	7572.77	410.55	509.78	6979.04	40.76	50.61	7469.17	58.81	73.02
High-40000	7071.42	476.03	591.08	9090.13	372.57	462.61	9254.94	129.74	161.10	9490.05	137.66	170.93
High-50000	9190.45	407.79	506.35	11674.26	387.85	481.58	11601.78	84.28	104.66	11835.06	109.59	136.07
High-60000	12138.48	386.16	479.49	15114.75	371.13	460.83	13887.54	129.67	161.00	13979.56	124.06	154.05

Table 26: Percentage of volume handled in planned wave

	Dynamic allocation						**Static allocation**					
	MIQP			*Simulation*			*MILP*			*Simulation*		
Scenario	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*
Low-15000	0.8695	0.0054	0.0067	0.8674	0.0057	0.0071	0.8653	0.0009	0.0011	0.8484	0.0046	0.0057
Low-20000	0.8314	0.0064	0.0080	0.8294	0.0054	0.0068	0.8322	0.0025	0.0031	0.8172	0.0072	0.0089
Low-25000	0.7931	0.0069	0.0086	0.7861	0.0027	0.0033	0.7953	0.0047	0.0058	0.7740	0.0018	0.0022
Low-30000	0.7529	0.0038	0.0047	0.7456	0.0035	0.0043	0.7475	0.0035	0.0044	0.7290	0.0026	0.0032
High-30000	0.9060	0.0007	0.0008	0.9049	0.0010	0.0013	0.9068	0.0008	0.0010	0.9058	0.0018	0.0022
High-40000	0.9234	0.0011	0.0014	0.9220	0.0015	0.0018	0.9259	0.0007	0.0008	0.9236	0.0016	0.0020
High-50000	0.9204	0.0049	0.0060	0.9165	0.0027	0.0034	0.9188	0.0027	0.0033	0.9129	0.0024	0.0030
High-60000	0.9028	0.0019	0.0024	0.8929	0.0021	0.0026	0.8983	0.0012	0.0015	0.8863	0.0023	0.0029

Table 27: Percentage of volume not handled

	Dynamic allocation			**Static allocation**		
	Simulation			*Simulation*		
Scenario	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*
Low-15000	0.0440	0.0018	0.0023	0.0429	0.0024	0.0030
Low-20000	0.0631	0.0023	0.0028	0.0614	0.0041	0.0051
Low-25000	0.0898	0.0045	0.0056	0.0898	0.0025	0.0031
Low-30000	0.1244	0.0021	0.0027	0.1204	0.0028	0.0035
High-30000	0.0066	0.0006	0.0007	0.0068	0.0009	0.0011
High-40000	0.0174	0.0010	0.0013	0.0172	0.0006	0.0007
High-50000	0.0363	0.0029	0.0036	0.0371	0.0021	0.0027
High-60000	0.0664	0.0032	0.0040	0.0640	0.0010	0.0013

A.9.2. Results planning horizon

Table 28: Planning horizon: number of sortation lane changes between waves

	Dynamic allocation		
	MIQP		
Scenario	*Mean*	*SD*	*CI +/-*
Month	14.0000	0.00	0.00
Week	15.0000	0.8944	0.3692
Day	11.3200	1.5930	0.6576
Updated day	11.9600	1.8435	0.7609

Table 29: Planning horizon: percentage of volume of orders sorted via internal sortation lane

	Dynamic allocation					
	MIQP			*Simulation*		
Scenario	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*
Month	0.2324	0.0202	0.0084	0.2856	0.0517	0.0213
Week	0.2459	0.0287	0.0118	0.2991	0.0644	0.0266
Day	0.2053	0.0406	0.0168	0.2578	0.0755	0.0312
Updated day	0.1837	0.0257	0.0106	0.2388	0.0769	0.0318

Table 30: Planning horizon: additional minutes spent on internal sortation lane

	Dynamic allocation					
	MIQP			*Simulation*		
Scenario	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*
Month	8865.74	819.66	338.34	10754.49	2210.64	912.51
Week	9393.73	778.22	321.23	11259.18	2604.11	1074.92
Day	7814.39	1296.69	535.25	9674.73	2718.72	1122.23
Updated day	6965.69	934.65	385.80	8933.39	2645.41	1091.97

Table 31: Planning horizon: percentage of volume handled in planned wave

	Dynamic allocation					
	MIQP			*Simulation*		
Scenario	*Mean*	*SD*	*CI +/-*	*Mean*	*SD*	*CI +/-*
Month	0.9116	0.0106	0.0044	0.9093	0.0097	0.0040
Week	0.9129	0.0108	0.0045	0.9107	0.0106	0.0044
Day	0.9123	0.0111	0.0046	0.9098	0.0104	0.0043
Updated day	0.9123	0.0111	0.0046	0.9096	0.0112	0.0046

Table 32: Planning horizon: percentage of volume not handled

	Dynamic allocation		
	Simulation		
Scenario	*Mean*	*SD*	*CI +/-*
Month	0.0167	0.0083	0.0034
Week	0.0175	0.0090	0.0037
Day	0.0175	0.0087	0.0036
Updated day	0.0173	0.0085	0.0035