MASTER

Simulation of storage strategies for a forward-reserve warehouse

Nataraja, Bhoomica

Award date:
2019

Department of Industrial Engineering & Innovation Sciences
Operations Planning Accounting & Control

Simulation of storage strategies for a forward-reserve warehouse

Master Thesis

Bhoomica M. Nataraja

Supervisors:
dr. Zümbül Atan, TU/e, OPAC
dr. Alp E. Akçay, TU/e, OPAC
Erik van der Hooft, vidaXL, Supply Chain Control

Eindhoven, August 2019

TUE, School of Industrial Engineering.
Series Master Theses Operations Management and Logistics

Subject Heading: Forward-reserve problem, Assignment and Allocation Strategy

Abstract

Fast-pick (forward) areas are commonly used in order picking warehouses to improve labour efficiency by conglomerating picking activities within a compact area, thus minimizing the distance travelled by the pickers. One problem that must be solved when a fast-pick area is present is the assignment-allocation problem. This problem deals with deciding which products (SKUs) should be assigned to the fast-pick area, and how much space should be allocated to them. This decision is complex and has a high impact on performance in terms of throughput and operational costs. This research was motivated by the picking operation of a fast-moving consumer-goods' distribution warehouse where a fast-pick area equipped with conveyor belt is in place. The goal of this work is to evaluate whether specific storage strategies could lead to a decrease in operational costs while maintaining the service level as high as possible. A discrete event simulation model is developed for the forward and reserve areas of the warehouse focusing on the order picking and replenishment processes and, in particular, the impact of storage space allocation on the performance. Computational experiments showed that by allocating an additional location for a product in the forward area, the picking time reduces significantly while the replenishment time increases slightly.

Preface

This master thesis is written as part of the master Operations Management & Logistics at the Eindhoven University of Technology. I performed this project at vidaXL, HaBa Trading BV, an international online retailer, from December 2018 to August 2019. During this thesis, I worked on improving storage process at one of the vidaXL's warehouses.

During this research, I got help and support from many people who I want to thank. First of all, I would like to thank my first supervisor, Zümbül Atan. I value her founded feedback and support during my project. Something that I truly appreciate is also the informal conversations we had. Additionally, I would like to thank my second supervisor, Alp E. Akçay, for his suggestions and feedback.

Besides the supervisors, I would like to express my gratitude to vidaXL for providing me with the opportunity to perform my research project in their warehouse. The colleagues at vidaXL helped me a lot with data and insights during the project. Finally, I want to thank Erik van der Hooft, supervisor from vidaXL, for guiding me throughout the process and helping me to focus on specific goals. I would also like to thank Saeid Zandi for his feedback and timely inputs.

Furthermore, I would like to thank my friends for the brainstorming sessions and being helpful. And special thanks go to my parents, who gave me love and support during my entire study career.

Bhoomica Nataraja
Eindhoven, August 2019

Management Summary

This research is conducted at one of the vidaXL's warehouses, MKI warehouse, situated in the Netherlands. MKI warehouse stores fast-moving-consumer-goods inventory from external suppliers for distributing to customers. The arriving products are stored as complete or partial pallets in the reserve area. The warehouse, equipped with a conveyor belt for material handling, includes two main product flows. The products following first flow are shipped as full pallets or picked piecewise and placed on the conveyor in the loading area. In the second flow, products are transferred to the fast-pick (forward) area, where the items are picked and placed on the conveyor that runs alongside the storage bins.

With this set-up, the management of vidaXL would like to evaluate if the current processes are efficient and how the operational costs can be reduced. The objective of this research was to expose the current bottlenecks and recommend solutions to improve efficiency. This led to the research question: What improvements does vidaXL require for conveyable items with respect to storage, replenishment, and picking processes to increase the warehouse efficiency given the limitations of the warehouse layout? In this research, efficiency is measured as the number of picks per hour (PPH) and warehouse cost per pick (WPP).

The research focuses on the evaluation of assignment and allocation strategies in order to reduce operational costs. The resources which are necessary for the picking process, such as the number of reachers (for replenishments) and the order pickers are varied to find a fitting workforce capacity. Storage assignment deals with the selection of SKUs to be stored in the fast-pick area, which could potentially lead to reduction in picking time. Storage allocation determines the quantities of each SKU, to reduce the number of replenishments of the pick locations, thus saving the capacity of the reach trucks. This problem is called the forward-reserve problem.

Situation at vidaXL

The following bottlenecks were observed after analyzing the current situation and interviewing stakeholders.

- Assignment of products to the fast-pick area: Current method of assignment selects the SKUs based solely on the monthly average demand. This method attributes to higher replenishment costs since lesser pallet norm (quantity of an SKU that can go on a pallet) can lead to more number of replenishments.

- Storage design in the fast-pick area: The double-deep bins in the forward area allocate two pallets of one SKU. However, there is a provision to split these bins to accommodate two half pallets of two SKUs. This option has not been explored.

- Allocation of bins to the products in the fast-pick area: An equal space allocation is in place, i.e., two-pallets of each product is stored in a bin. However, the allocation can be varied to reduce picking costs by accommodating more SKUs in the fast-pick area or reduce replenishment costs by giving more bin space to certain SKUs.
- Picking sequence in the reserve area: Due to the use of tow tractor with single-sided roll cages for picking in the reserve area, every aisle is visited twice to pick from left and right. Furthermore, the turn radius of the tow tractor disallows turning in the middle of an aisle. This potentially increases the travel time of the picker.

Design

The design of fast-pick area for vidaXL is built using two-step approach, assignment and allocation, explained as follows. Besides the storage policies in the fast-pick area, changes to the picking route sequence in the reserve area is proposed.

- Fast-pick area bin design: Foremost, a change to the bin design in the fast-pick area is suggested in order to adopt different storage strategies. This change allows storing of twice the number of SKUs in the fast-pick area. However, based on the total costs, limited number of bins can undergo this change.
- Assignment: The current assignment strategy based on popularity is evaluated to form a baseline of performance. Two alternate assignment methods Economic Assignment Quotient (EAQ) and Labour Efficiency (LE) are proposed. Putting the group of SKUs chosen by these methods will decrease the total material handling costs and there by WPP.
- Allocation:The products chosen from the assignment strategies need at least one location in the fast-pick area. However, not all SKUs need to be stored in the fast-pick area. The simulation model determines the number of locations (one or two pallet norm space) for each SKU that would decrease the total costs.
- Picking route in reserve area: Currently, the warehouse follows a single-sided picking strategy for picking in the reserve. A double-sided picking strategy is proposed which results in a significant decrease in the picking time.

Results and Conclusion

The proposed strategies are tested using a discrete event simulation model which is a digital replica of the MKI warehouse. The best performing scenario is able to decrease the total material handling cost by 19.2% with 1256 bins in the fast-pick area. Furthermore, sensitivity analysis is performed to determine a reasonable set of workforce capacity and to understand the influence of input parameters such as labour cost, activity time and replenishment threshold on the output costs. Inclusion of new picking strategy in the reserve area resulted in 26% decrease in the material handling costs and 956 bins in the fast-pick area. Additional recommendations have been given to minimize the replenishment movements in the warehouse.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Warehouse management plays a substantial role in ensuring that the entire supply chain system functions efficiently. With the support of comprehensive warehouse services, any company can respond to the clientele demands better. A warehouse can be defined as a material handling station dedicated to receiving, storing, order-picking, accumulating, sorting and shipping of goods (Van den Berg & Zijm 1999). Warehouses can be broadly categorized into distribution, production and contract warehouses (Van Den Berg 1999). One of the vidaXL warehouses at Venlo, MKI warehouse, is a distribution warehouse wherein the products from external suppliers are collected (and sometimes assembled) for delivery to customers.

vidaXL handles fast-moving consumer goods within MKI warehouse. This warehouse has a complicated set-up, and thus, any design change must be evaluated based on the total cost of ownership to make a business case. Furthermore, the management has many ideas about potential improvements but carrying out real-world experiments would be time-consuming, cost inefficient and risky. Hence, there is a need for a model that can test and quantify the improvements.

The aim of this research is to provide an operation oriented simulation model that could help managers in assessing the performance of different storing and picking strategies. In particular, the developed model must signify a replica of the current warehouse design and facilitate the testing of different policies and scenarios for future use. Conclusively, outcomes and recommendations must form the basis for a new implementation plan.

This chapter provides further background on vidaXL (section 1.1). Chapter 2 will outline the problem structure at vidaXL. Chapter 3 describes the established practice at vidaXL and the analysis of current situation is explained in Chapter 4. Literature relevant to this research is presented in Chapter 5. The design of the model which could be implemented at vidaXL is given in Chapter 6. Chapter 7 describes a simulation model with which the design is tested. Chapter 8 presents the results obtained by the proposed strategies, and finally, Chapter 9 provides the conclusion.

1.1 Company Background

vidaXL is a rapidly growing international online retailer offering thousands of for in and around the home products. vidaXL was established in 2006 when the founders Gerjan den Hartog and Wouter Bakker started selling products on e-Bay. Soon, they started developing their own branded products and selling these to consumers over the internet. The assortment proliferated, and now vidaXL is competing worldwide to offer products at lower prices than their competitors.

vidaXL controls the complete chain from production to shipping, which allows them to offer the products at competitive prices. vidaXL collaborates with 800 factories (supply base) worldwide and is equipped with a workforce of approximately 1400 employees globally. The company was able to generate annual revenue of a quarter billion Euros in 2017.

vidaXL covers sales and operates distribution centres (spanning a total of 139000 m^2) in Europe, the United States of America and Australia. European region contains four operating distribution centres in Venlo and one at Venray, The Netherlands.

MKI warehouse, based at Venlo, handles a broad assortment for the European market. The products are classified into ten main product types (Table A.1) based on the dimensions, shape and storage criteria of the products. vidaXL keeps widening its product portfolio to meet the demand of the customers and gain market share in an ever-changing market. The 23000 products, offered by vidaXL on the web shops, consist of own-brand products as well as other brand products. vidaXL aims to deliver all products right from stock, which means that the warehouse stores almost every article.

Chapter 2

Research structure

This chapter describes the research structure of this project. It elaborates on the problem definition (section 2.1) and scope (section 2.2) of this research. The project approach for solving the problem definition is added in section 2.4.

2.1 Problem Definition

The objective of this project is to help supply chain team at vidaXL to evaluate alternate storage strategies to increase the warehouse efficiency. In September 2018, a conveyor belt system was installed at MKI warehouse to increase the picking efficiency. However, changes such as the increase/decrease in the number of products, the introduction of new products or scrapping of obsolete products influence the storage strategy that, in turn, affects the efficiency/throughput. Due to the addition of new customers or new products, the number of pick tasks would increase, whether the warehouse will be able to process this increase depends on two key parameters: 'available pick time' and 'time per pick task'. With these two parameters, there are two possible cause and effect relation.

1. If the time per pick task stays the same and the number of pick tasks increases, then the available pick time has to increase. Available pick time can be increased by hiring additional pickers.

2. If the available pick time remains the same, i.e., there is no option to hire new pickers, the only logical opportunity to handle the increased demand is to decrease the time per pick task.

Furthermore, the conveyor system divides the warehouse into fast-pick and reserve areas, due to which the current set-up of MKI warehouse in SAP EWM (extended warehouse management) software is quite complicated. Each design change or new strategy must be evaluated based on the total operational cost to build a business case. Thus, it is essential to quantify every improvement.

The complicated set-up of the MKI warehouse does not facilitate immediate change of the policies employed for put-away, storage and picking. In this situation, different questions arise: Are the current operational processes efficient? What alternatives could reduce operational costs? What changes to the storage strategies in the warehouse or SAP would increase efficiency?

Chan & Chan (2011) identify four tactical and operational decisions that influence the efficiency of a warehouse:

- Layout design: layout of the facility containing the order picking system and layout within that order picking system.
- Picking policies: how the orders to be picked are grouped or batched for a picking tour.
- Storage assignment policies.
- Routing policies: the sequence of items to be picked during any tour.

Most of the warehousing professionals identify order picking as the highest-priority activity in the warehouse for productivity improvements. The reasons for this consideration are: First, order picking is the costliest activity in a typical warehouse. 55% of all operating costs in a typical warehouse can be attributed to order picking (Tompkins et al. 2010) (see Figure 2.1); Second, incorporation of more SKUs in the order picking systems may dramatically lead to an increase in the throughput, storage and picking accuracy requirements; Third, these requirements lead to more labour requirements or investment in automated equipment.

Order picking and replenishment are considered the expensive and labour intensive activities in any warehouse. This research integrates picking and replenishment to generate a storage strategy that minimizes the operational costs and increases warehouse efficiency. In general, efficiency is a measurable concept, quantitatively determined by the ratio of useful output to total input. Efficiency provides a comparison between what is really being performed with what can be performed taking into account the same amount of resources, such as: money, time and labour.

In this research, efficiency will be measured in the form of number of picks per hour (PPH) and warehouse cost per pick (WPP). PPH is a simple calculation of picks carried out divided by hours worked, which also provides a basic guide to productivity. PPH is usually tracked over time and used to calculate the resources needed to complete the daily workload. (Example: if the average PPH is 100 units per picker per hour and the operation needs to pick 100,000 units in 12 hours, then to complete the task, 84 pickers are required.) WPP is essentially the same as PPH, but using cost rather than time. The calculation total cost of picking and replenishment divided by number of units picked provides an average warehouse cost per unit picked. The aim will be to drive the cost part of the calculation down so that the average unit costs less than previously which in turn would potentially reduce the time taken per pick.

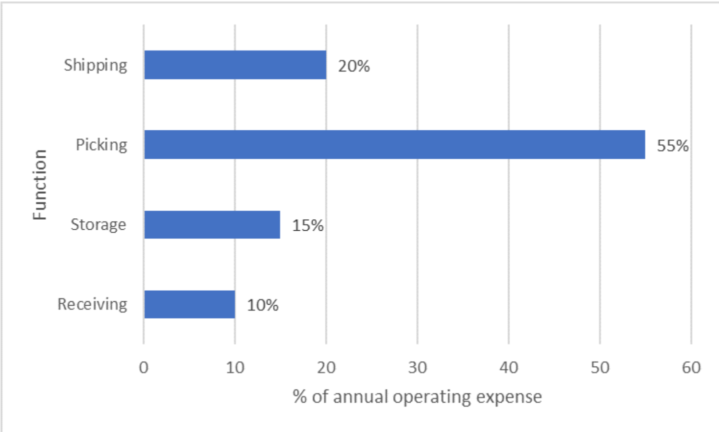


Figure 2.1: Typical distribution of warehouse operating expenses (Tompkins et al. 2010)

2.2 Scope

In this research, the warehouse efficiency is improved through optimization of design parameters for storage strategy in MKI warehouse. As the focus of this study is on the storage design alteration, only feasible changes in layout design of the warehouse will be investigated. The scope includes order-picking, storage and replenishment processes for two product types: fast-moving conveyable and slow-moving conveyable products.

The problem definition presented in this section is formulated based on interviews with relevant stakeholders and by conducting data analysis on the raw data provided by the company. Based on this information, the main problems identified are low picking productivity and low storage availability for fast-moving conveyable products.

2.3 Research Questions

2.3.1 Research Question

The main research question addressed through the execution of this project is:

What improvements does vidaXL require for conveyable items with respect to storage, replenishment and picking processes to increase the warehouse efficiency given the limitations of the warehouse layout?

2.3.2 Sub-questions

The project further answers the following sub-questions framed in the research proposal document.

1. What are the KPIs used by vidaXL to assess the performance of processes involving conveyable items?

2. What is the current performance in relation to the selected KPIs?

3. What are the bottlenecks that significantly affect the KPIs?

4. What are the design parameters and policies that can be changed to improve the KPIs given the limitations of the warehouse design and SAP EWM compatibility?
    (a) What are the design parameters and policies related to a storage area that can be changed?
    (b) How can picking efficiency be increased by integrating the new storage policy?
    (c) How can the replenishment movements be minimized to maintain the picking efficiency?
5. How do the proposed changes affect the KPIs?

2.4 Research Approach

The following plan-of-action is carried out in the execution of this research.

1. Exploration and empirical validation of the business problem:
    (a) Investigation of the current processes concerning the conveyable product range.
    (b) Identification of the KPIs at vidaXL related to the project.
    (c) Investigation of the current performance at vidaXL by using the identified KPIs.
    (d) Validation of the problem according to the current targets held by vidaXL.
2. Diagnosis of the problem:
    (a) Identification of causes that constitute the problem and affect the identified KPIs.
    (b) Selection of causes to make improvement proposals based on the current performance and historical data.
3. Search for relevant literature.
4. Development of a simulation model as a solution design.
    (a) Validation and verification of the model.
5. Conducting simulation runs and selecting the design parameters which improve the performance.
6. Project documentation and presentation.

Chapter 3

Current situation

This chapter describes the current situation at the warehouse of vidaXL. The current layout of the warehouse is shown in section 3.1. The main warehouse processes, relevant to this research, storing and order picking are described in sections 3.2 and 3.3 respectively.

3.1 MKI Layout

MKI DC spans about $70,000m^2$ ($100,000m^2$ including the floors) and is a state of the art warehouse in Venlo with a material handling conveyor (equipped with a labelling machine and a sorting mechanism) that adds speed and efficiency to the warehousing and shipping operations. Previously, the warehouse processed up to 25,000 orders every day without the conveyor belt. Now, the conveyor belt alone handles 65,000 parcels every day at full utilization. This warehouse acts as a supply base for all the European sales areas in collaboration with other distribution centres and handles 90% of the vidaXL's entire product portfolio.

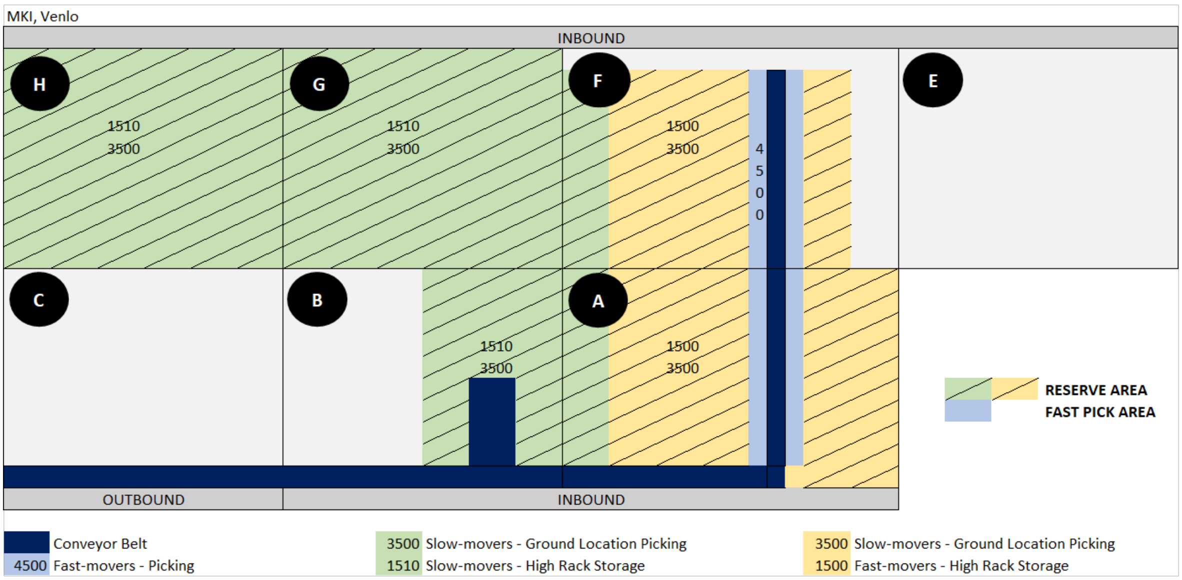


Figure 3.1: MKG Warehouse layout

An overview of the layout of the warehouse is given in Figure 3.1. The warehouse is segregated into seven halls, in which hall C is the outbound area and other halls are reserved for inbound and return processes. The warehouse is further divided into two main areas:

- Reserve area: This area comprises of sections 3500, 1500 and 1510. The reserve area is used to store full pallets to achieve the goal of high space utilization. A part of the picking process is also carried out in the reserve area.

- Fast-pick (forward) area: Fast-pick area is denoted by section 4500. The fast-pick or the forward area is a relatively smaller storage area equipped with three levels of conveyor belt system, and typically used for fast order picking.

The following are the material flows in MKI warehouse.

1. Flow 1 (receiving → reserve area → shipping): The full pallets received are stored in the reserve area. A part of the order-picking operation is performed, as further explained in section 3.3.2. Products under this flow are referred as slow-moving conveyable SKUs (slow-movers).

2. Flow 2 (receiving → reserve area → forward area → shipping): Products received at the inbound area are stored in the reserve area typically in pallet loads and then moved to the forward area for fast order picking. These products are called as fast-moving conveyable SKUs (fast-movers).

The conveyor belt in the fast-pick area moves the fast-movers from halls A and E to the outbound area situated in hall C. Another conveyor belt in the reserve area transfers slow-movers from hall B to the outbound area situated in hall C. vidaXL has its own logistic service as well as works with several third-party logistic providers to deliver the orders to the final customer.

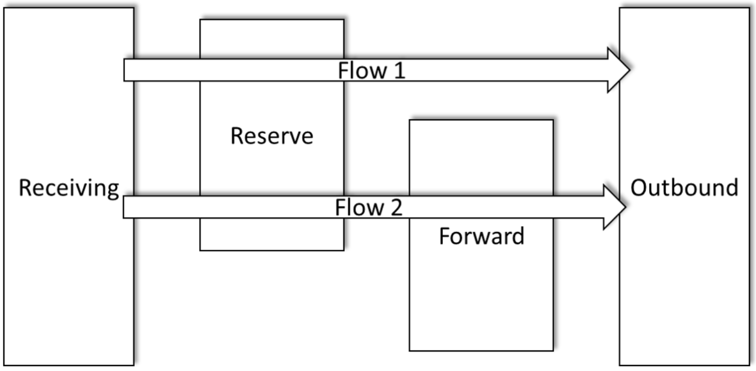


Figure 3.2: Product flows within MKI warehouse

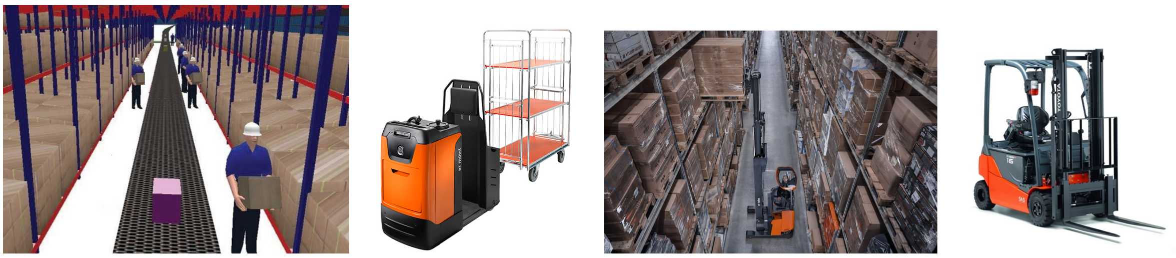
3.1.1 Material Handling Equipment

vidaXL warehouse has a number of handling equipment at their disposal to undertake the picking process. These range from relatively cheap trolleys through mechanical equipment to conveyor system. Some of the equipment used in picking operations are as follows.

- **Conveyor systems**: Conveyor systems are used for moving cartons/trays through the picking area and beyond. Fast-moving and slow-moving conveyable products pass through the conveyor belts in hall A and hall B, respectively. Currently, there are 828 storage locations made available in 3 floors on both the sides of the conveyor belt in hall A and F for the fast-moving SKUs as illustrated in Figure 3.3a. The slow-moving items are picked in waves and then brought to the loading point of the slow-moving conveyor belt in hall B. The conveyor system is further equipped with a labeling and sortation system. As each labelled item passes a barcode reader it is identified and diverted to a particular location on route. The items slide down a chute and are loaded directly onto a vehicle.

- **Towing tractors for low-level order pickers**: These tractors are used for picking in the reserve area. Low-level order-picking trucks are electrically powered and have the facility of moving two pallets or up to three roll cages at a time along picking aisles (Figure 3.3b). These trucks are able to operate at first and second levels with operator being lifted upwards on a platform. The towing tractors are ideal for horizontal transport, i.e., they make S-shaped travel through the aisles and cannot be turned around in the middle of an aisle.

- **Reach and electric fork trucks**: These trucks (figures 3.3c and 3.3d) have a reaching mechanism that extends and retracts to store and retrieve pallets. They can access both single-deep and double-deep racking positions and thus, support the whole process of pallet movements across the halls.



(a) Conveyor belt (Hall A and F) (b) Tow tractors (c) Electric Reach Truck (d) Electric fork lift

Figure 3.3: Material Handling Equipment

The warehouse is equipped with regular pallet racks and pallet flow racks for storing the goods in the reserve area and fast-pick area respectively. vidaXL handles different kinds of pallet dimensions due to a wide range of products. Table B.1 in Appendix B provides the different storage bins and pallets used in the warehouse. For every SKU and every pallet, a pallet norm (number of items that can go on a pallet) is calculated, and the best fit pallet is selected for storage.

3.2 Storing Process

This section provides the details on the storing and replenishment of the goods in the reserve area and fast-pick areas.

3.2.1 Storing in the reserve area

Products in the reserve area are stored according to a section-based closest-open storage policy. As soon as the receiving process is completed at the inbound area, SAP determines the closest-open bin in the respective sections and allocates the products to this location. vidaXL uses the following sections, as shown in Figure 3.1.

- **3500**: This section consists of both single-deep and double-deep bins. Ground and first level locations in the reserve area consist of the slow-moving items. These items are picked using tow tractors with the roll cages. SAP generates a replenishment task when the pallet is empty. Additionally, few partial pallets of fast-movers are stored in this area.

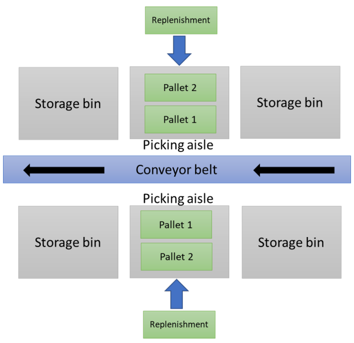
- **1510** (single-deep): Slow-movers are stored in the higher levels of the racks (high-rack area) and are used to replenish bins in 3500.

- **1500** (double-deep): Fast-movers are stored in the high rack areas and used to replenish bins in the fast-pick area (4500).

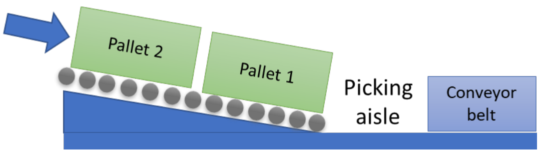
The dimension of the racks are different, and the pallet must fit in these rack dimensions. Due to the use of different types of pallets, there is a possibility of under-utilization of the bins.

3.2.2 Storage in fast pick area

MKI warehouse employs a dedicated storage strategy in the double-deep fast pick area (4500). Each SKU that is stored in the fast pick area has a fixed storage bin. Section 4500 has a total of 828 storage bins on three levels of pallet flow racks along both sides of the conveyor belt. Each bin has a self-replenishing mechanism (pallet flow rack) i.e., as soon as the first pallet is removed from the bin, the second pallet moves down automatically to the front for picking (Figure 3.4b). Brake rollers keep gravity under control and ensure that the pallet at the front is never under impact pressure from the following pallet. An order picker traverses along the conveyor belt, picks from the bins and places the picked item on the conveyor belt.



(a) Fast pick area



(b) Pallet flow racks

Figure 3.4: Fast Pick Area

3.2.3 Replenishment Process

The replenishment process in pick locations of both the reserve and fast pick areas is automatically generated by SAP. The system checks for the stock levels after confirmation of the pick tasks during the pick wave. The stock quantities are reduced in SAP as and when an item is picked. In the reserve area, SAP triggers a replenishment task when the pallet quantity is zero. In the fast pick area (double-deep), the SKUs have two pallet places. When the first pallet is empty, and the second pallet reaches 60% of the pallet norm, a replenishment task is triggered. When these replenishment levels are reached, SAP triggers replenishment tasks that consist of the source location in the reserve area 1500 or 1510 and the destination pick location in 4500 or 3500. If the high rack storage locations (1500 and 1510) in the reserve area have no more pallets for replenishment, they are released automatically for allocation of other items. Reachers equipped with reach trucks or forklifts carry out the replenishment tasks and place the pallets in the requested bin locations.

3.3 Order Picking Process

The company adopts an accumulation/sorting (A/S) system. Items of a group of orders (a *pick-wave*) that are to be loaded onto a certain number of trucks are picked from the picking area. In general, items from the same order are assigned to multiple order pickers (to maintain high order picker efficiency), and the order pickers follow pre-specified routes to pick the items assigned to them. After picking, order pickers place their items on the transportation conveyor and the items are transported to the label applicator and then to the sorter. Owing to the assignment of orders to more than one order picker, the items of each order arrive at the sorter in a random sequence. The sorter releases the items into their assigned shipping lanes.

3.3.1 Order picking in the fast pick area

The order pick process in fast pick area uses zone-wave picking. There are 4 zones in each level of section 4500. Logistics planner releases the queues of picking tasks in a wave according to the shipping schedule. Pickers are assigned a zone and a queue, and each picker picks SKUs that are stocked in their zone. During each pick, order picker traverses through the picking aisle indicated in Figure 3.4a, picks one item at a time from the storage bins and places it on the conveyor belt. Daily, the logistics planner releases three waves through SAP system. The first wave starts at 6:00 am, the second wave at 11:00 am and the third wave at 1:00 pm. If there are more shipments to be sent, another wave is released between 4:00 pm and 6:00 pm.

3.3.2 Order picking in the reserve area

The order pick process in the reserve area is segregated into two types.

1. Full pallet pick: This is a simple process in which a reach truck picks a full pallet and places it at the loading area.

2. Case pick: This process uses a tow tractor with roll cages to go through the aisles for picking. These roll cages are open on the left side and thus, allows only single-sided picking. Due to this constraint and the large turn radius of the tow tractor, a sequence of routing is predefined in SAP.

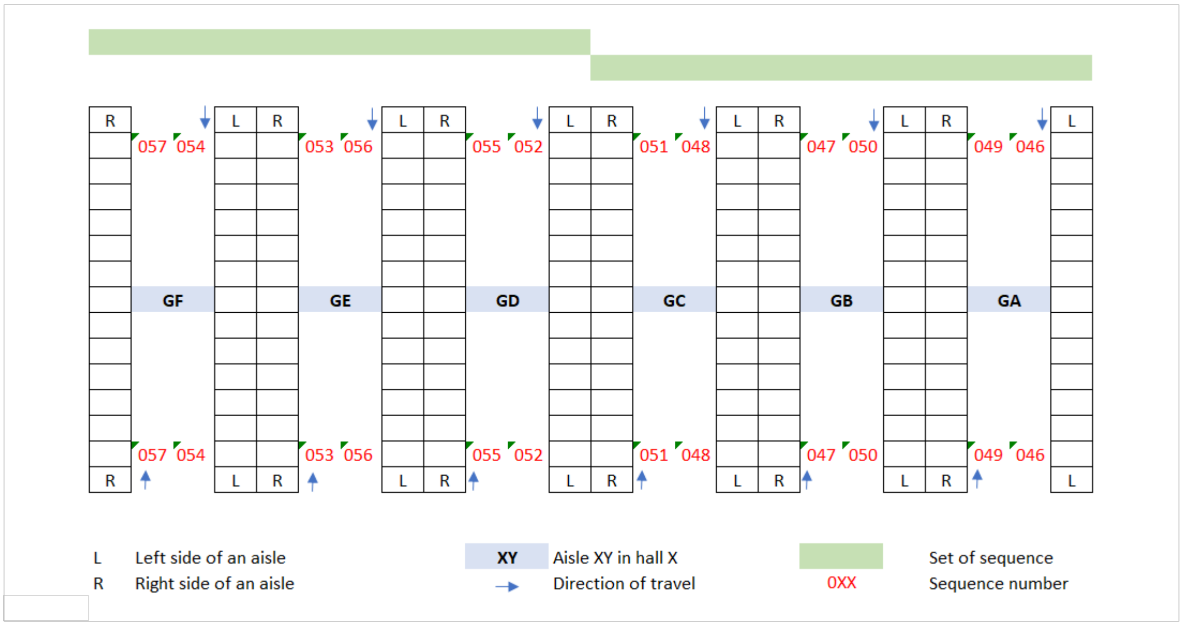


Figure 3.5: Picking route sequence for reserve area in halls B and G

Figure 3.5 illustrates the sequence used for picking in the reserve area. For example, an order picker travels through aisels GA, GB and GC following the number 046 through 051 and picks from the left side of the aisles. Sequence numbers are combined into sets indicated by the green blocks. Once a picker completes picking from this, he/she goes to the loading point at Hall B to load the items on to the conveyor belt.

3.4 Summary current situation

The current situation in the MKI warehouse is described in this section. The first section briefly outlines the layout of the building and the equipment used. The storage, replenishment and order picking processes are explained briefly with illustrations to give a clear insight into the current situation. This section acts as a starting point to identify the current bottlenecks.

Chapter 4

Current performance

This chapter provides an answer to the sub-questions 1 (What are the KPIs used by vidaXL to assess the performance of processes involving conveyable items?), 2 (What is the current performance related to the selected KPIs?) in section 4.1 and 3 (What are the bottlenecks that significantly affect the KPIs?) in section 4.2. Finally, the observations and analyses are summarized in section 4.3.

4.1 Current KPIs

This section describes the Key Performance Indicators (KPIs) used by the supply chain control team at vidaXL. The calculation is based on the data gathered from SAP EWM (warehouse management) and SAP BI (data warehousing) tools.

4.1.1 Warehouse utilization

This KPI determines the warehouse occupation per storage type and is measured for fast-moving conveyable products stored in the storage sections 1500, 3500 and 4500. Utilization is calculated as the ratio of the number of items that are stored in a storage type to the actual capacity (Pallet Norm) of that storage type. From the plot in Figure 4.1, it is evident that the utilization of section 1500 is around 70%. The partial pallets of fast-movers stored in section 3500 use around 40% of the storage space. The fast-pick area (4500) has a utilization rate of around 60%. This lower utilization rate may be due to two reasons: (1) An SKU assigned to a fixed-bin in 4500 is no more a fast-mover, and since 4500 follows a dedicated storage strategy, SAP disallows storage of any other SKU item in that bin; (2) The replenishment of the allocated item takes a long time due to delays from external suppliers.

To avoid under-utilization, the proper allocation of products in the fast-pick area is necessary. The fast-movers which become slow-movers must be removed from the fast-pick area. However, the management executes this change slowly to reduce the warehouse movements such as change of pallets due to different rack dimensions. Furthermore, warehouse utilization is a high-level analysis and cannot be used as an indication of inefficiency.

4.1.2 Picking percentage

Figure 4.2a represents the picking percentage calculated per product type. For this computation, it is considered that one pick is equal to one order. The proportion of slow-movers

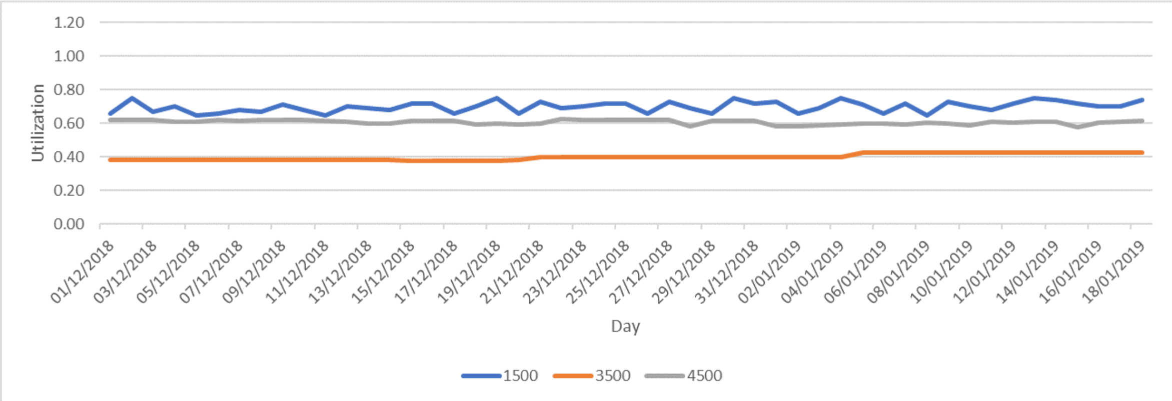
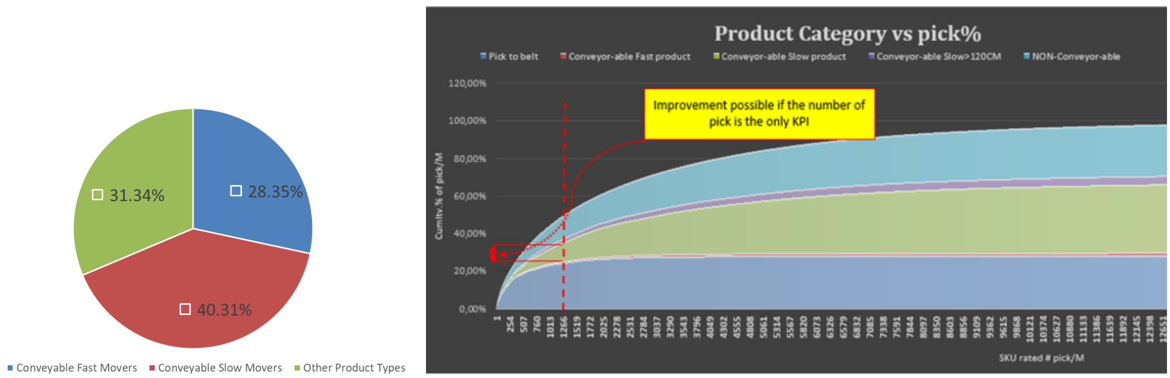


Figure 4.1: Warehouse Utilization by Fast Movers per Storage Type

picked is more than that of fast-movers which means that an increase in the number of fast-movers would help to improve the picking percentage and utilize the conveyor belt at its best for maximum throughput. Practically, the fast-pick area can accommodate 828 fast-moving products. Due to obsoleteness or low demand of products, the existence of slow-movers in fast-pick area allows picking of only 25% fast-movers. The Pareto chart in Figure 4.2b also suggests that there is a room for improvement, i.e., an increase in the pick percentage of fast-movers by 10% when 1266 products (current 828 fast-movers + next 438 fast-movers that are currently slow-movers) are placed in the fast-pick area.



(a) Picking per Product Type

(b) Pareto Analysis of Picking per Product Type

Figure 4.2: Effect of customer class priority and demand lead time on average costs.

4.1.3 Replenishment rate

Replenishment rate is the number of replenishment actions carried out per hour. Currently, the reachers at MKI warehouse perform tasks such as put-away, replenishment, pallet picks and other miscellaneous tasks in an hour. Miscellaneous tasks consist of removal of empty pallets from the fast-pick area and reshuffling of bins. On average, a reacher is expected to perform 20 replenishment tasks in one hour, but not all the reachers are achieving this target.

Figure 4.3 gives the replenishment actions confirmed by various reachers throughout the day (snapshot of 22/01/2018) and an average number of replenishments per hour is calculated based on how many hours a reacher works. The work efficiency of a reacher cannot be changed, however, the number of hours dedicated for replenishment will be an input in this research.

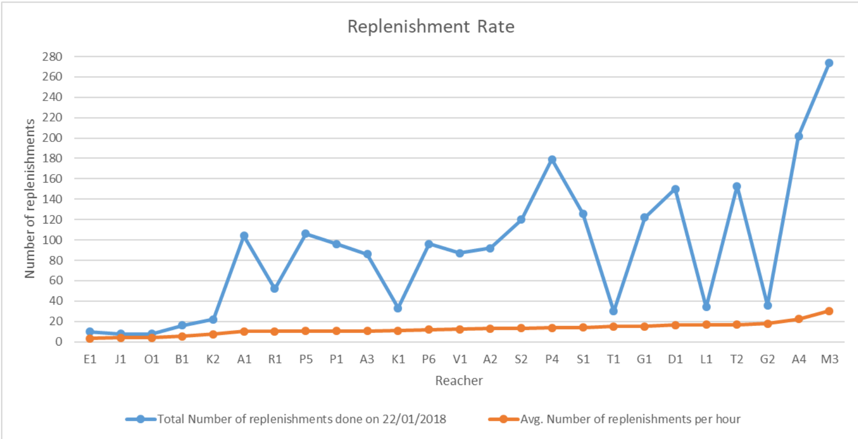


Figure 4.3: Replenishment rate

4.1.4 Monthly warehouse cost

The finance department calculates this KPI every month depending on the demand, the number of workers and equipment. They calculate the personnel cost based on the hours logged by the warehouse employees on PEP (workhours logging) system and their hourly rates defined by the staffing agencies. 76% of the warehouse costs incurred is due to the personnel costs (see Figure 4.4). Reachers and order pickers contribute to 9.66% and 10.1% of the total working hours logged by the warehouse employees, respectively. Though these numbers look small, the cost of the resources is high, which makes it necessary to determine the right number of resources required in the warehouse. Moreover, any change to the storage policy would make a significant change in the number of workers required.

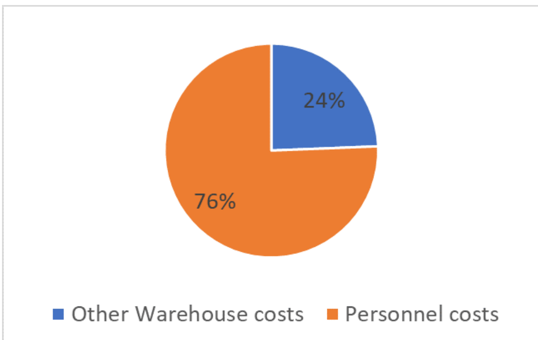


Figure 4.4: Warehouse Costs 2018

Table 4.1: Current Key Performance Indicators

Indicator	Performance measure	Definition
Utilization	1. Warehouse utilization	Utilization per section, i.e., the average amount of warehouse capacity used over a specific amount of time
Productivity	2. Picking percentage	Ratio of number of times a product type is picked to the total number of picks
	3. Replenishment rate	Number of replenishment actions done per hour
Costing	4. Warehouse cost/month	Cost of personnel and equipment involved in warehouse operations

4.2 Bottlenecks and KPIs

The KPIs maintained in the current situation by the company is insufficient to address the research problem. Furthermore, parameters that influence the discussed KPIs must be identified. Hence, the first step is to define the bottlenecks in the current situation and the second step is to measure the performance and calculate the KPI related to the bottleneck.

4.2.1 Bottlenecks

The bottlenecks in the current situation are identified by analyzing data from the SAP system and observing processes in the warehouse. The following causes are identified based on the discussion with the stake holders of vidaXL.

Assignment of products to the fast pick area

The current procedure involves the following steps:

1. The supply chain control team calculates the monthly average demand of a product based on one year's demand, assuming that each demand is equal to one pick.
2. Products with a coefficient variation more than one are eliminated.
3. The remaining products are ranked in decreasing order of monthly average.

The first 828 products are then considered fit to be fast-movers. However, not all of these 828 products are put in the fast-pick area. Considering the number of movements resulting by changing the products in fast-pick area, only 6 to 10 products are changed.

Further, an analysis of the pick tasks data for two months is shown in Figure 4.5. The products are ranked by the descending values of their number of picks. The product with the highest number of picks gets the first rank. 300 and 200 slow-movers are picked more than a fast-picker in January and February respectively. It is observed that the distance the picker traverses in the fast-pick area is less than the distance traversed in the reserve area. Thus, inappropriate assignment of products in the fast-pick area results in a higher number of picks in the reserve area and less saving opportunities that the forward area can provide.

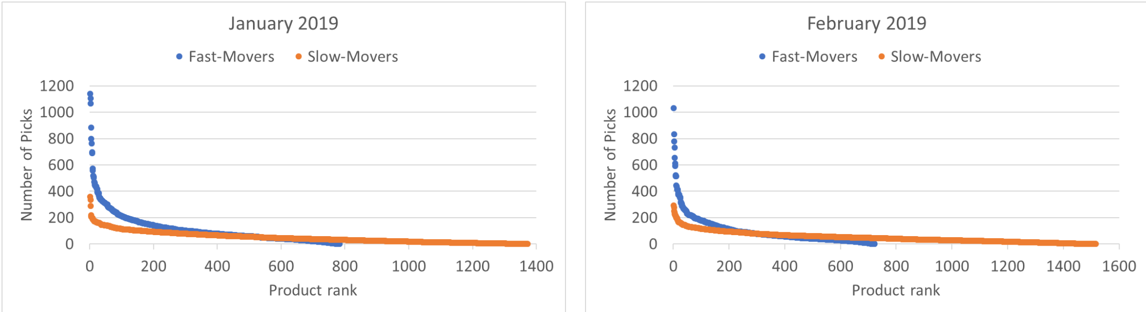


Figure 4.5: Number of Picks per product

Therefore, in summary, the problem arises due to improper attribution of fast-movers and slow-movers which leads to incorrect assignment.

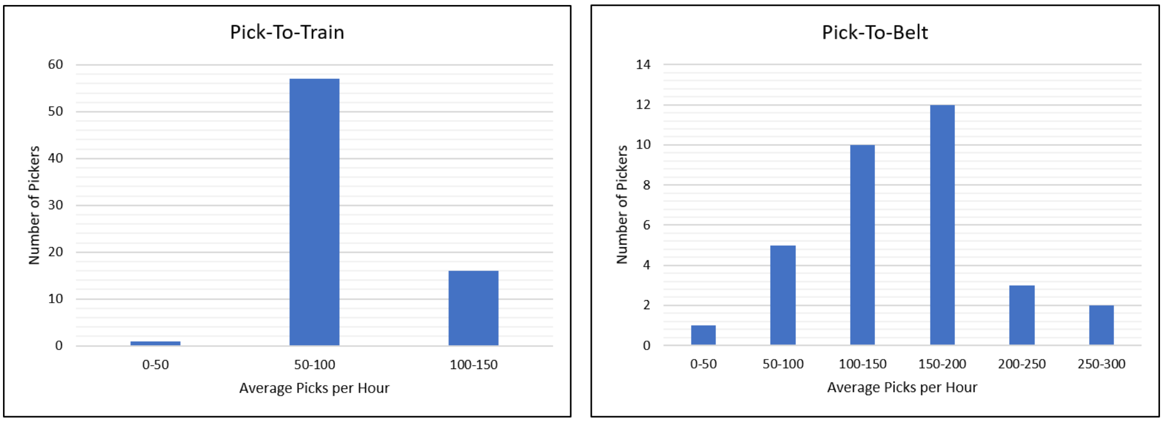
Storage design in the fast pick area

The double-deep bins in the fast-pick area (4500) have a height of 2.1 m and currently, can store two pallets of E21 or B21. With this design, 828 storage locations are available. This limitation hinders the storage of more fast-moving products during the high season. However, there is provision to decrease the bin heights to obtain two bins out of a bin. These decreased bins can then accommodate four pallets of E09 or B09 or a combination of the two. Pallet types are defined in Table B.1. However, this approach increases the number of replenishment tasks. Therefore, the number of bins in the fast-pick area plays a significant factor in picking efficiency.

It is evident from Figure 4.2b that there is a possibility to increase the picking percentage by increasing the number of bin locations in the fast pick area. Picking productivity can be determined to ensure that the picking efficiency increases by placement of products in the fast-pick area. Picking productivity is the total number of products picked per labour hour. An analysis of a month's data of the average picks per hour is presented in Figures 4.6a and 4.6b for reserve area (3500) and fast-pick area (4500) respectively. Most of the pickers in fast pick area pick 150-200 items per hour while the pickers in the reserve area pick 50-100 items per hour. Again, there is room for possible improvement for the outflow of the products if some of the potential slow-movers are stored in the fast-pick area.

Allocation of bins to the products in the fast-pick area

Currently, equal space allocation is the strategy employed. For each fast-mover, two pallets are placed in the fast-pick area. The number of replenishments required for this assignment is not evaluated while making the decision. It is necessary to estimate how many spaces should be allocated to the products to increase the picking efficiency and minimize the possible replenishments at the same time.



(a) Picking Productivity (3500)

(b) Picking Productivity (4500)

Figure 4.6: Picking Productivity

Picking sequence in the reserve area

Due to the usage of single-sided roll cages, a reserve area picker must travel the aisles twice. Single-sided picking is usually recommended for wide aisles, and high volume picks. However, this is not the case in halls B, G and H, since they have narrow aisles and the turn radius of the tow trucks don't allow turning in the middle of an aisle. Further exploration on the picking sequence for single-sided picking or other alternatives would prove beneficial.

Workforce Capacity

From a cost perspective, a fast picking area reduces labour time dedicated to order picking. However, it is also a fact that it requires more frequent replenishments from the reserve area, thus, increasing the replenishment labour. At MKI warehouse, the capacity of the reach truck is approximated based on the forecasted demand. Unfortunately, it is hard to track down the actual labour hours spent by a reacher for replenishment, because a reacher carries out various tasks (put-away, pallet pick and replenishment) at the same time. This randomness makes it difficult to decide whether the capacity of the reachers is too high or too low, and cannot be tracked with the available data. The reach truck capacity will affect the replenishment time. It would be useful to see whether the variation of reach truck capacity could yield a saving.

Similarly, the performance of a picker varies from time to time (Figure 4.6). Any issues with RF guns could halt the work. The number of pickers required at each level in the fast pick area varies from one to four. The more the workers at a level, the shorter the travel time. It may be beneficial to find a tradeoff between the number of pickers and total pick time.

4.2.2 Required KPIs

The bottlenecks lead to labour-intensive work. Besides the assignment and allocation strategy, the company lacks activity-based costing calculations. If each picking and reach movement is assigned a cost, a savings based analysis can be beneficial in finding the right products to be placed at the fast-pick area. Thus, the KPIs calculated, in this research, are the total number of labour hours spent on picking and replenishment in fast-pick and reserve areas.

Another problem is the limited number of bins available in the fast-pick area. If the number of bins is increased, more fast-movers can be stored in the fast-pick area and the picking hours can be reduced. The goal is to estimate the optimal number of bins that minimizes labour hours. Furthermore, time taken for picking in reserve area will be used to analyze picking routes for pickers in the reserve area.

4.3 Summary current performance and bottlenecks

The observation, information gathered from SAP and interviews with the employees at vidaXL is summarized as a cause & effect diagram. Figure 4.7 illustrates the fish-bone diagram of the analysis based on the format created by Ishikawa. The causes fall under the factors 6Ms of six sigma process (man, machine, material, method, milieu and measurement).

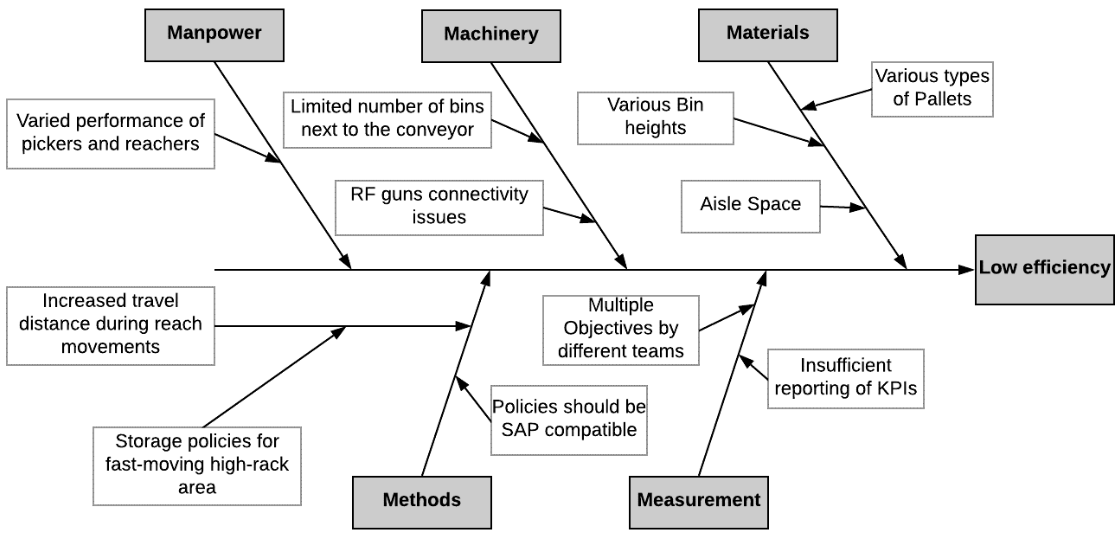


Figure 4.7: Cause-and-effect diagram for the research problem, based on the 6Ms of six sigma

Chapter 5

Literature study

Within the literature, different aspects are viewed to address the problem. This chapter contains the relevant literature for solving the bottlenecks explained in section 4.2.1. The first two sections deal with two of the main critical issues faced in design and management of order picking system: storage allocation and storage assignment. Storage allocation determines the right inventory level per each SKU and storage assignment deals with the selection of SKU to the fast-pick area. Further, literature on one-sided picking is briefly explained in section 5.3.

5.1 Assignment

The first bottleneck, which SKU to store in the fast pick area, involves reducing both picking time and costs. The storage assignment problem has been formalized by Frazele & Sharp (1989) and classified as a non-polynomial (NP) hard problem. Due to the nature of the fast-picking areas where every item needs to be assigned a specific location, as would be in the case of pallet flow racks, dedicated storage is the most used policy in warehouse. The literature presents several storage assignment strategies for dedicated storage policy.

Hackman et al. (1990) stated that a dedicated/reserved storage can be assigned based on activity rather than mere availability. This way, order pickers can learn more easily where the products are situated. Two commonly used assignment rules for dedicated storage area are:

1. Popularity: Popularity is defined as the number of storage/retrieval operations per unit time. This rule considers a list of items sorted by decreased value of popularity (i.e. from the highest popularity to the lowest), then assigns the most popular to the most desirable location (Gu et al. 2007).

2. Cube per Order Index (COI): COI is the ratio of the maximum allocated storage space to the number of storage/retrieval operations per unit time. This policy considers both the SKU's popularity and its storage space requirement. The storage space requirement depends on the stock of the SKU and the number of locations the stock requires. Items are ranked by increasing COI value; the lowest value is assigned to the most desirable location (Gu et al. 2007).

Gu et al. (2007) stated that if a unit load occupies the same amount of storage space, the COI policy is essentially the same as the popularity policy. The model in (Gu et al. 2007) considers that additional expense for material handling for restocking the forward area as storage in the forward area is less than that in the reserve area.

Hackman et al. (1990) presented a heuristic that uses a ratio called *Economic Assignment Quotient* (EAQ), which is the ratio of the annual number of request R for item i and the square root of its annual demand D, $\frac{R_i}{\sqrt{D_i}}$. The heuristic ranks the products based on their EAQ - highest to lowest - and assign optimal quantities to the forward area for each product.

Bartholdi III & Hackman (2008b) formulated an equation to determine the savings per SKU i per year. If the net benefit per year for SKU i is positive, the SKU should be stored in the fast pick area.

$$\text{Net benefit per year per SKU } i = sp_i - c_r d_i \tag{5.1}$$

s = Savings in minutes of pick a SKU from the fast pick area instead of the reserve area
p_i = Number of less than 75% of a pallet quantity per year (popularity)
c_r = Time of restocking, minutes
d_i = Number of restocks per year

5.2 Allocation

Hackman et al. (1990) first modelled the *forward-reserve problem* using knapsack-heuristic to determine which products and in what quantities must be placed in the *forward* or *fast picking* area. To minimize the total costs for order-picking and replenishment, they used EAQ ratio which transforms the assignment-allocation decision into a simple ranking problem.

The assumptions made by Hackman et al. (1990) are similar to the situation in MKI warehouse: (i) The pick quantity for SKU i in the forward area is always less than the full allocation of an SKU in the forward pick area. (ii) A restock is scheduled when the inventory level of bins drop to a certain threshold.

Gu et al. (2010) evaluated the gap between the (Hackman et al. 1990) greedy heuristic and optimal solution. They concluded that this gap is negligible for real world problems, where the number of SKUs is large enough. Frazelle et al. (1994) employed the heuristic into a framework to determine the optimal size of the forward area, also incorporating congestion constraints and parameters being dependent on the storage volume. They inferred that the model reduced the congestion in the warehouse by minimizing the activity in the forward area. Further, they went on to prove that the procedure developed by Hackman et al. (1990) resulted in a 20% saving on labour cost by re-sizing the forward area and reallocating the products among the forward and reserve area.

Bartholdi III & Hackman (2008a) introduced and compared three different strategies for inventory levels for the fast-pick area, namely equal space strategy (EQS), equal time strategy (EQT) and optimal strategy. Table 5.1 illustrates the analytical models of their evaluation. Opt strategy dedicates each SKU the proper fraction of available storage volume that minimizes the total number of replenishments to the forward area, as argued by Hackman et al. (1990).

Further, Bartholdi III & Hackman (2008a) formulated the *labour efficiency ratio* based on the EAQ. The ratio represents the marginal net benefit measured in total labour (picking and replenishment) of assigning an item to the forward area. They demonstrated that using

Table 5.1: Storage allocation strategies (Bartholdi III & Hackman 2008a)

Allocation strategies	Inventory level (%)	Description
Equal space (EQS)	$v_i = \frac{1}{n}$	Same storage volume per each SKU
Equal time (EQT)	$v_i = \frac{f_i}{\sum_i^n f_i}$	Same number of restocks per each SKU
Optimal (OPT)	$v_i = \frac{\sqrt{f_i}}{\sum_i^n \sqrt{f_i}}$	Minimize the total number of restocks

Notes: v_i : average percentage inventory level for SKU i; f_i : demand (volume) of SKU i in a period of time; n : total number of SKUs.

conventional methods such as Equal Time Allocation and Equal Space Allocation yield greater benefits. They compared labour efficiency to COI (Cube-per-Order Index) and argue that the COI strategy fails to consider replenishing costs in the assignment of items, and therefore, is just a measure of picking efficiency, but not of labour efficiency.

Bartholdi III & Hackman (2008a) developed a model where the size of the bins is variable. For vidaXL this is not possible, since the products are arranged on fixed size pallets during receiving process. Van den Berg et al. (1998) designed a model which use fixed size pallets for replenishment to minimize replenishments during the picking period.

The aforementioned literature addressed continuous space allocation of the forward-reserve problem. Walter et al. (2013) relax the assumption of continuous space forward area and solve the discrete forward-reserve problem for assignment, allocation and sizing of the fast picking area. However, they do not solve these three problems simultaneously. They investigate the problem with equal size bins, each containing only one SKU and assume that SKU i can be stored with a_i number of units in a bin. These assumptions coincide with the problem addressed in this research.

5.2.1 Number of bins

The separation of the warehouse into fast-pick and reserve areas creates the forward-reserve problem. There exists a direct relationship between the number of bins in the forward pick area and the number of replenishment. As the number of bins increases, the picking costs increase, and the replenishment cost increases or vice-versa. However, this relationship depends on two decisions: (i) which SKUs to assign to this area and (ii) quantity of these SKUs to allocate to this area.

5.3 One-sided picking

In one-sided picking, a part of the items are picked while traversing the aisle in one direction and the remaining items are picked while traversing the aisle in the other direction. This routing policy is also called as "split traversal policy".

One-sided order picking attributes to large travel distances. Goetschalckx & Donald Ratliff (1988) developed an efficient optimal algorithm and showed that policies yield up to 30% savings in travel time over commonly used policies. It is also shown that, for narrow aisle widths, it is significantly more efficient to pick both sides of the aisle in the same pass rather than pick one side and then pick the other side, unless the number of pick locations per aisle is very large or the aisles are very wide. The latter condition applies to MKI warehouse.

De Koster et al. (1999), in their case study, also obtained a substantial reduction in walking time by changing from one-sided picking to two-sided picking in the narrow aisles.

5.4 Summary

Some of the studies presented presuppose a "continuous space model", where a portion of a storage bin can be allocated to an SKU. However, this is not applicable at MKI warehouse. SKUs can only be stored in discrete units, and a continuous distribution of space can only be an approximation of reality. Approximating the solution of continuous space model may also assign the ineligible slow-movers with very small space (close to zero), to the fast-pick area. Consequently, the eligible ones leave the set of SKUs of forward area or get fewer bins. To avoid these shortcomings, this research uses storage rules that result in a discrete space output.

Chapter 6

Research design

The purpose of this research is to find a model for evaluating storage assignment strategies in the fast-pick area to maximize the order picking efficiency. This chapter describes the design of the *static discrete* assignment, allocation and the simulation methods used in this research. The term static suggests that the decisions about the forward area are made periodically (monthly). This approach disregards the SKU's demand trends during the planning horizon. Thus, in the static forward-reserve problem, the demand represents the total demand of an SKU during the past year.

This chapter explains the experimental design adopted in this research. The method used for analysis and evaluation is presented in section 6.1. Section 6.2 summarizes the design parameters and their notations. Finally, the scenarios that are evaluated in this research are explained in section 6.3.

6.1 Methodology

Simulation has often been used to optimize warehouse design and operations. Gagliardi et al. (2007) developed a discrete-event simulation model to evaluate storage space strategies in a high-throughput warehouse. Similarly, Faria & Reis (2015) employ a discrete-event simulation model to evaluate various storage and routing strategies to improve order picking performance. Pawlewski (2015) present a methodology to reduce the time necessary to build the simulation model of a big distribution centre. They solve an Order Picking problem with simulation methods using commercially available simulation and optimization software packets. Following these works, a discrete-event simulation model is employed in this research for evaluation. The following procedure defines the methodology of building the simulation model of the analyzed warehouse:

1. Preparation of the warehouse layout from the CAD diagram.
2. Identification (cataloguing) of resources and modelling: static - racks, bins, paths, conveyors; dynamic - operators, forklifts.
3. Addressing (x, y and z coordinates) - aisles, racks, shelves and bins.
4. Creation of picking lists (historical or random).
5. Concept of replenishment- first, racks having infinite capacity and later, modelling the real replenishment.

6. Motion launch - the first simulation model, based on points 1 through 5.
7. Model Validation.
8. Definition of function goals.
9. Definition of decision variables.
10. Preparing scenarios.
11. Optimization Experiments.

6.2 Design parameters

Each strategy uses different variables that emphasize various characteristics of the warehouse. However the picking and replenishment costs are determined with the same parameters:

- p_i (pick tasks of SKU i per year): 33445 conveyable SKUs are obtained and referred as set P. This data is is received from the supply chain control team. One unit of an SKU will be picked per pick task.
- $norm_i$ (pallet norm of SKU i): The pallet norm is fetched from the product master data in SAP. Pallet norm is the number of units of an SKU that can be loaded on a pallet.
- v_i (volume of SKU i, pallet/unit): Assuming that equally sized pallets are stored in the bins, the volume of an SKU unit will be, $v_i = \frac{1}{norm_i}$. For example, if the pallet norm of an SKU is 20 units/pallet, then one unit of the same SKU occupies a volume of $\frac{1}{20}$ pallet/unit in the bin.
- d_i (annual demand in pallets): The flow of pallets is represented by d_i which is expressed as $d_i = p_i v_i$.
- Cost of picking in the warehouse, seconds: The hourly wage for a MKI warehouse picker, covering an 8-hour shift, is €XP[1]per hour. The simulation model is run with the historical data of six months and the time per pick is estimated as follows:
  - c_{pf} (cost of picking in the forward area): It takes 17.126 ± 0.167 seconds (based on 95% Confidence interval) to pick a product in the fast-pick area with 2 pickers on each level. This time includes the time taken to reach the item location, scan, pick the product from the bin and place it on the conveyor. Thus, one pick from the fast-pick area costs, on an average, XX[1] cents.
  - c_{pr} (cost of picking in the reserve area): With 4 pickers in the reserve area, time taken per pick is 58.233 ± 2.328 seconds. This time includes the time taken for: traveling to the product location, scanning the bin, picking, placing in the roll-cage, travelling to the conveyor and placing on the belt. Thus, a cost of XX[1] cents per pick is obtained.
- c_s (cost savings per pick in the forward area, seconds): This is the cost saved by picking in the forward area, i.e. $c_s = c_{pr} - c_{pf}$. Here, saving is expressed in terms of time, for calculation of labour efficiency assignment strategies.

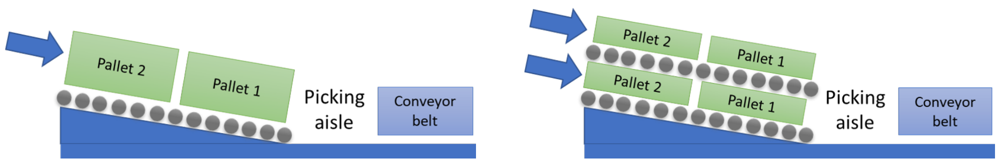
- c_r (cost of replenishment in the warehouse, seconds): Average hourly wage of a reach truck operator is €XR[1]. Similar to picking, based on the simulation runs from historical data, time taken per replenishment is estimated as 201.218 ± 3.561 seconds (based on 95% confidence interval). This yields a cost of €XX[1] for one replenishment.
- n_{bin} (number of bins): This parameter represents the number of bins in the fast-pick area with a range [828,1656].
- n_{pf}: Number of order pickers in the fast-pick area. Since there are three levels in the fast-pick area, this number is varied in multiples of 3.
- n_{pr}: Number of order pickers in the reserve-area. The current routing sequence method comprises of 10 sets of bin sequence in halls B and G. Depending on n_{pr}, these picking sets are assigned to the picker.
- n_r: Number of reachers in the warehouse. There is no segregation in the reachers working for the fast-pick and reserve areas.

6.3 Scenarios

This section provides the scenarios that will potentially result in an improved order picking efficiency. These scenarios are tested using the simulation model described in Chapter 7.

6.3.1 Number of bins

The fast-pick area in MKI warehouse has three levels and these levels collectively accommodate 828 storage bins. Each storage bin is assigned one SKU and stores two pallets (double-deep) of the respective SKU as shown in Figure 6.1a. These bins can be horizontally split to make 1656 double-deep bins which can accommodate two smaller pallets each consisting of half pallet norm of an SKU. Figure 6.1b illustrates the new bin design. However, all the bins need not be split and this can be determined through a reasonable storage strategy. Thus, n_{bin} is varied to determine the optimal number of bins.



(a) Current bin design (b) Proposed bin design

Figure 6.1: Storage bin design in fast-pick area

6.3.2 Storage assignment and allocation

The storage assignment and allocation policies found in the literature are put to use in this section to develop test scenarios. A list of 33445 SKUs that are conveyable and currently

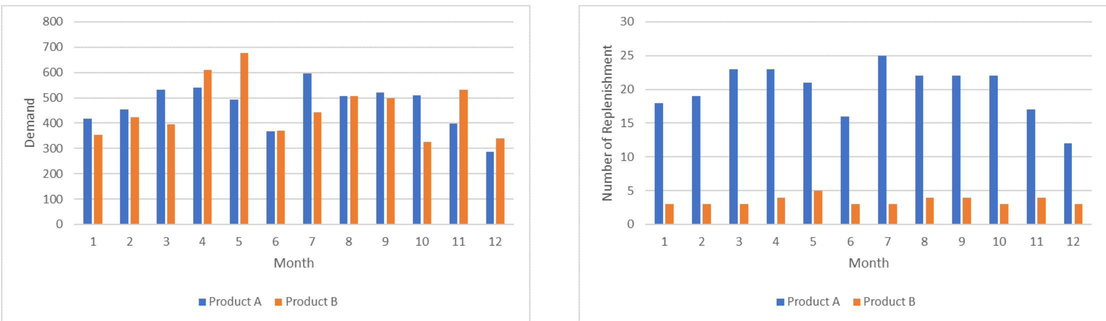
[1]Cost has not been revealed due to confidentiality reasons.

classified as fast-movers or slow-movers is received from the supply chain control team. For each SKU, the pallet norm (quantity of SKU that can go on a pallet), demand and number of picks in the last six months are fetched from the SAP EWM system. The maximum number of products that can go onto the fast-pick area is 1656. Assuming that SKUs are ranked from 1 to 1656 and the bin variation starts with $n_{bin} = 828$ bins, the 829^{th} SKU is allocated by splitting 828^{th} bin into two. So, the SKUs 828 and 829 would be having the proposed bin configuration. With this consideration, the set of SKUs are obtained from the following assignment methods, and allocation steps are carried out during the simulation. It is assumed that the minimum and the maximum number of bins allocated to an SKU is one and two respectively.

Method 1: Established method

The current allocation of SKUs to the fast-pick area is based on the demand data. Average monthly demand and co-efficient of variation (CV) of all the SKUs are calculated. SKUs with a CV higher than one are eliminated to avoid allocation of obsolete and highly variable products to the fast-pick area. SKUs are ranked in the decreasing order of their average monthly demand. This method is equivalent to the popularity index strategy.

Apart from the presence of slow-movers in fast-pick area and fast-movers in reserve area as discussed in section 4.2.1, there is another drawback. This method does not consider the number of replenishment required by a product. Consider two products A and B, which have demand, as shown in Figure 6.2a and an average monthly demand of approximately 462 units/month. However, product A and B have different pallet norms, 24 and 160, respectively. The lesser the pallet norm, the higher the replenishment. Product A has a higher number of replenishments than that of B (Figure 6.2b). The current method is considered as the baseline for comparing other scenarios, and the first 1656 SKUs are considered based on the current method of ranking.



(a) Demand

(b) Replenishment

Figure 6.2: Demand and replenishment under current storage strategy

Method 2: Economic Assignment Quotient (EAQ)

The EAQ procedure and the Hackman et al. (1990) heuristic for solving assignment and allocation problem have been modified for this research and summarized in three steps:

1. Rank all SKUs in order of non-increasing EAQ : $\frac{p_i}{\sqrt{d_i}}$. EAQ can be simplified as follows.

$$EAQ = \frac{p_i}{\sqrt{d_i}} = \frac{p_i}{\sqrt{p_i v_i}} = \frac{p_i}{\sqrt{p_i \frac{1}{norm_i}}} = \sqrt{p_i \cdot norm_i} \tag{6.1}$$

2. for $i = 1 : |P|$ do

   (a) Let z_i be the volume of SKU i to be assigned to the forward area. Use equation 6.2 to compute the space allocation vector $z = z_1, \ldots, z_i$ corresponding to the set of $S_i = 1, \ldots, i$ SKUs in the forward area.

$$z_i = \frac{\sqrt{d_i}}{\sum_{j \in S_i} \sqrt{d_j}} n_{bin} \tag{6.2}$$

   (b) Use equation 6.3 to calculate the total benefit for each set of S_i.

$$\sum_{i \in S_i} sp_i - c_r \frac{d_i}{z_i} \tag{6.3}$$

   end for

3. Select the set of S_i which yields a maximum value of total profit satisfying constraint $\sum_{i \in S_i} z_i \leq n_{bin}$.

Method 3: Labour efficiency (LE)

Bartholdi III & Hackman (2008b) formulate the forward-reserve problem as an instance of *Knapsack problem*, by selecting SKUs for forward storage with a decision variable $x_i \in \{0, 1\}$. With an objective to minimize the total labour cost subject to the space constraint that only n_{bin} storage bins are available in the forward-pick area. The formulation, where l_i is the minimum number of locations required by sku i in the fast-pick area, is as follows:

$$min \sum_{i=1}^{|P|} (c_{pf} p_i + c_r d_i) x_i + c_{pr} p_i (1 - x_i) \tag{6.4}$$

$$\sum_{i=1}^{|P|} l_i x_i \leq n_{bin} \tag{6.5}$$

$$x_i \in \{0, 1\} \tag{6.6}$$

The objective can be rearranged to obtain an equivalent form with savings ($c_s = c_{pr} - c_{pf}$).

$$max \sum_{i=1}^{|P|} (c_s p_i - c_r d_i) x_i \tag{6.7}$$

Bartholdi III & Hackman (2008b) further propose a Greedy Heuristic which involves ranking the SKUs by "bang-for-buck" independent of n_{bin}. In the context of forward-reserve problem, bang-for-buck is the labour-savings per forward location, which they term as *labour* *efficiency*. Labour efficiency is given by equation 6.8. SKUs of largest labour-efficiency (labour savings per location) have priority for storage in the forward area.

$$\frac{(c_s p_i - c_r d_i)}{l_i} \tag{6.8}$$

Bartholdi III & Hackman (2008b) present the following procedure to decide what goes into the fast-pick area, and in what amounts. The procedure involves the evaluation of the net cost : charge each SKU for each of its p_i and for each of its d_i restocks.

- Sort all SKUs from most labour efficient to least.
- Successfully evaluate the total net cost of putting no SKUs in the fast-pick area; putting only the first SKU in the fast-pick area; only the first two SKUs; only the first three; and so on. Choose the strategy that minimizes net cost.

6.3.3 Workforce

The designed allocation strategy relates to the capacity of the reach trucks, since the capacity of the reach trucks affects the replenishment time. It would be useful to see how the reach truck capacity influences the model and whether a saving can be made by increasing reacher capacity. The replenishment cycle time will be lower by adding capacity, however, the cost of resources will increase. Thus, along with the number of bins and the SKU sets, the number of pickers (n_{pf} and n_{pr}) and reachers (n_r) are varied to analyze the trade-off between the time taken for completion of tasks and cost.

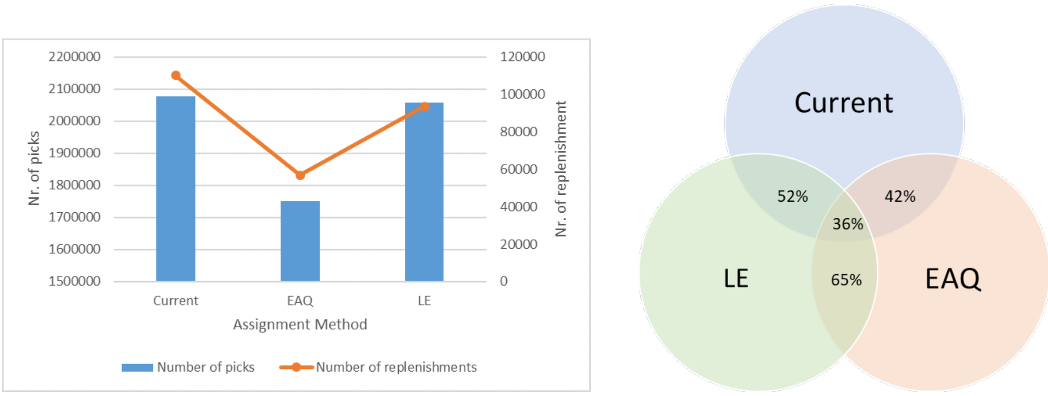
6.3.4 Routing sequence in reserve area

The established picking route sequence for section 3500 (reserve area picking) is suitable for one-sided picking. This can possibly change to a two-sided S-shaped picking policy (Figure 8.8), where a picker will visit each aisle and pick from either side of the aisle. The entire simulation and sensitivity analysis will be conducted with the current picking sequence. However, a simulation will be run to determine the savings yielded by two-sided picking.

6.4 Evaluation of Assignment Methods

The assignment methods explained in section 6.3.2 are applied to the given SKU list. Historical picks for each SKU is fetched from SAP EWM tool, to calculate the parameters in the assignment strategies. From each assignment strategy, 1656 SKUs are selected based on their ranking. Based on the historical data, the three assignment methods lead to different number of picks and replenishment tasks as shown in Figure 6.3. Figure 6.3b represents the number of common SKUs obtained from the first 828 selected SKUs among each method. If the company plans to adopt a new assignment strategy, say labour efficiency method, then, 46% of SKUs stored presently in the 828 bins have to be shuffled.

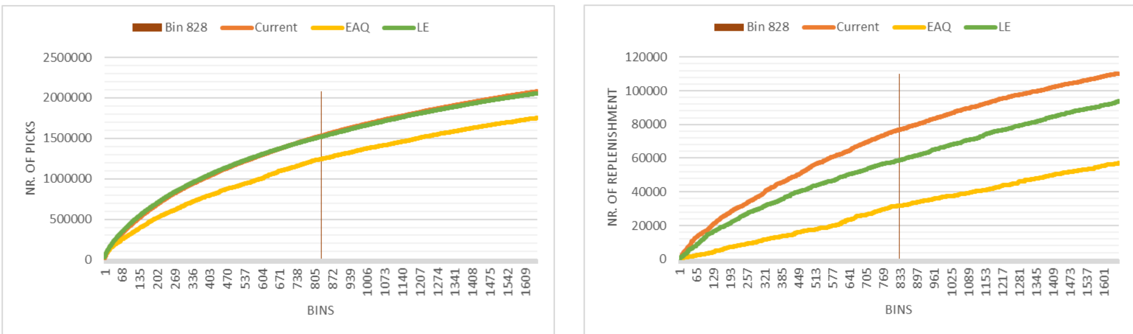
From Figure 6.3a, it can be observed that EAQ strategy offers less number of picks and replenishment tasks than the current method by storing all the 1656 SKUs in the fast-pick area. However, LE method results in almost the same number of picks as the current method but a significantly lesser number of replenishment tasks. This is evident in the plots illustrated



(a) Resulting tasks (b) Common SKUs

Figure 6.3: Results from assignment methods

in Figure 6.4 which shows the cumulative picks and replenishment tasks for every addition of an SKU. Since, the aim is to have as many picks as possible in the fast-pick area, the EAQ method is simulated for limited scenarios. Additionally, EAQ method leads to 64% change of SKUs in the fast-pick area which leads to labour intensive activities. The current method is evaluated and the obtained metrics are kept as a baseline for comparison of the LE method.



(a) Cumulative pick tasks (b) Cumulative replenishment tasks

Figure 6.4: Cumulative picks and replenishment tasks vs. SKUs

Figure 6.5 shows the distribution of labour efficiency for the set of SKUs obtain from the three assignment methods. Only about the top 700 SKUs would save significant labour time if picked from the fast-pick area. On a closer look in Figure 6.6, it can be seen that the SKUs with rank>1200 based on the LE method, yield considerably good labour savings. However, the savings of SKUs from EAQ method drops towards zero. SKUs ranked between 1200 and 1300 by the current method yield the labour savings equivalent to that from LE method. But, the next 200 SKUs do no have much effect on the labour costs. It would clearly be uneconomical to include any of the bottom 100 SKUs in the fast-pick area. Interestingly, this latter group may include the most important SKUs, those that are very popular and that move in great volume. However, storing such SKUs in the fast-pick area is inefficient. For

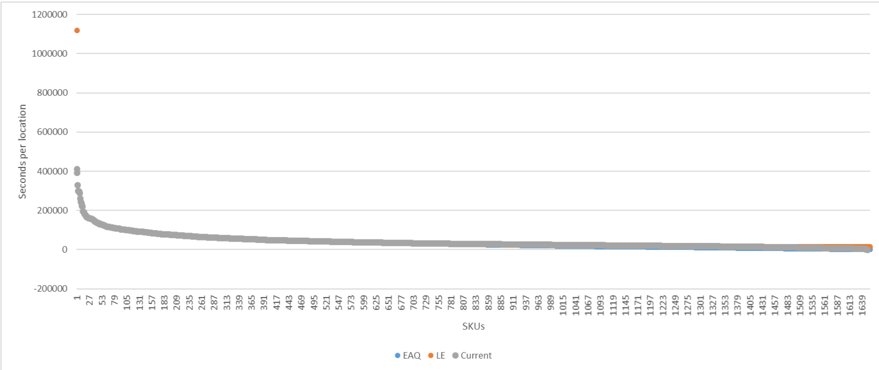


Figure 6.5: SKUs ranked by labour efficiency

example: Consider an SKU B with such a demand that an average pick is for half a pallet ($norm_B = 2$), then there are only about 2 picks per pallet before replenishment. Each pick of SKU B saves 41.12 seconds of picking, and costs 201.2 seconds for restocking. This results in a net loss of 88.96 seconds. Such a SKU should not be stored in the fast-pick area, even if their volume movement is high.

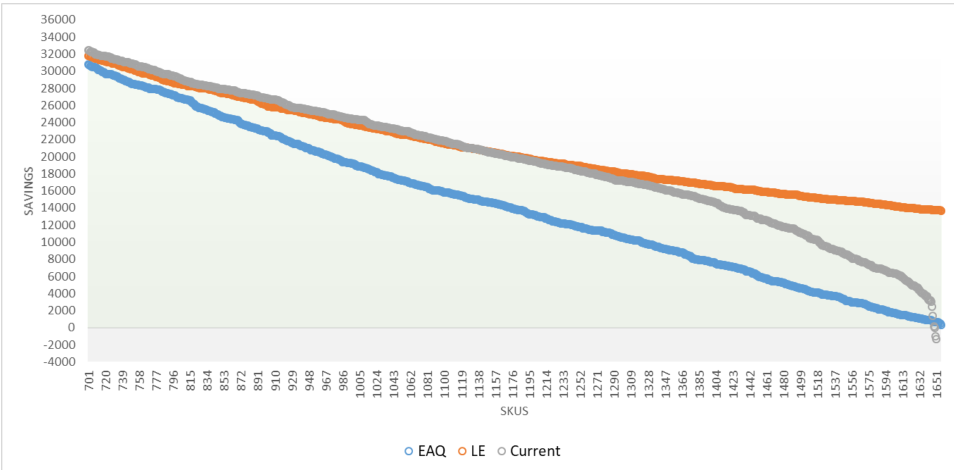


Figure 6.6: SKUs with rank > 1200

The result obtained in Figures 6.5 and 6.6 are by allocation of one pallet location to each SKU and in decreasing order of their savings. In order to further understand how these storage assignment methods lead to a saving, allocation of SKUs (1 or 2 pallet locations) is implemented in Chapter 8.

6.5 Summary

This chapter introduced the methodology employed for simulation in this research. It introduced, by using the literature review, multiple scenarios/variants which potentially result in an improved picking efficiency. The next chapter will describe how the used simulation model looks like and will therefore evaluate the discussed scenarios.

Chapter 7

Simulation model

In this chapter, the simulation model used to evaluate improved storage strategies is discussed. Simulation is introduced in section 7.1. The model description and framework are explained in sections 7.3 and 7.3.2 respectively. Further, section 7.4 will describe the procedure used to verify and validate the simulation model.

7.1 Introduction

Simulation is an extensively used technique for warehouse performance evaluation in the academic world as well as in practice. The simulation model, in this project, primarily uses Discrete Event Simulation (DES) method, since process-centric modelling is used widely in logistics and warehousing in particular (Borshchev 2013). The simulation model implemented in AnyLogic Simulation Modeling Software is based on the Java framework. In this framework, the simulation entities are partitioned into three major categories, namely Statics, Dynamics and Events. Static elements have constant properties which describe the diced physical warehouse layout. Dynamic elements have modifiable properties describing mutable entities such as pickers, SKUs, and picking lists. Finally, Events modify the states of the Dynamic entities and are executed sequentially according to the logic configuration. The software has an integrated shortest-path routing module, based on Dijkstra's algorithm (Dijkstra (1959)), facilitating smooth set up of pickers and reachers.

Figure 7.1 illustrates the experiment flow. The simulation model is used to evaluate and compare various strategies. Firstly, actual demand data and inventory locations are obtained. The physical layout of the warehouse is also translated into the simulation model; the physical layout is constant throughout all the experimental runs. For each set of demand data, the simulation is run using the sets of SKUs obtained by the different storage strategies. Parameters such as the number of bins, pickers and reachers are subjected to a design of the experiment. The established storage assignment is also implemented in the simulation model to compare the current situation with the improved storage with an outflow of products of six months.

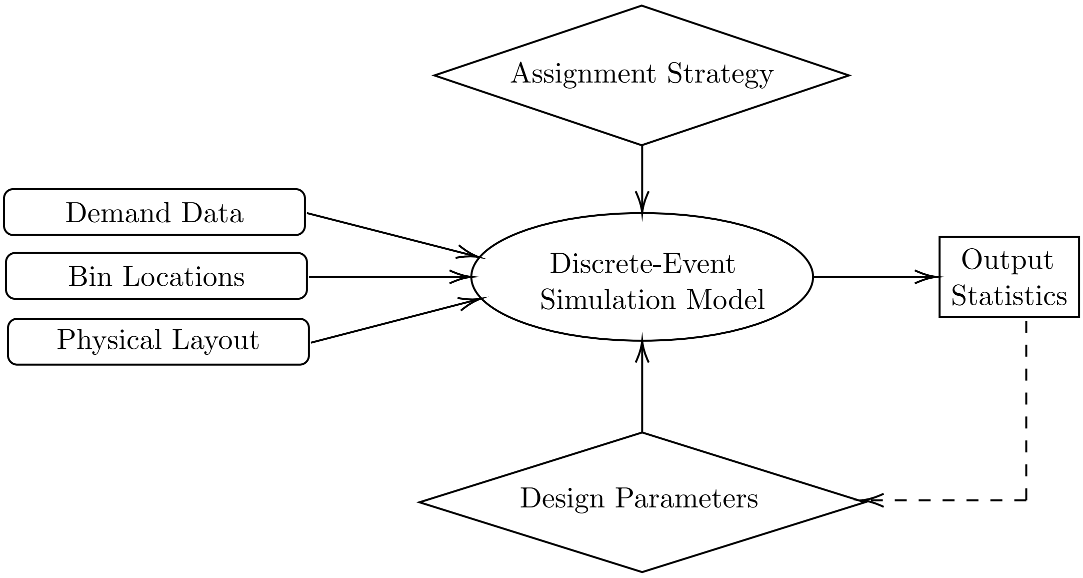


Figure 7.1: Simulation Experiment Flowchart

7.2 Assumptions

The following assumptions are made in the model.

1. If an SKU is assigned to the forward area, then all picks for that product are performed from the forward area.

2. Every time a replenishment task is triggered, a full pallet is replenished to the fast-pick area.

3. Concurrent replenishment and order-picking activities in the reserve area do not cause congestion. AnyLogic transporter library allows conflict-free routing in the model.

4. The warehouse layout including the position of bins remains the same throughout the simulation.

5. A pick task comprises of only one item of an SKU.

6. The picker processes only one pick task at a time.

7. Time taken for put-away is equal to the time taken for replenishment.

8. It is assumed that the reserve area has an infinite capacity since the customers cannot order, in turn, pick tasks are not created if there is no stock in the warehouse.

7.3 Model description

This section describes the simulation model developed for this research.

7.3.1 Model objectives

The main objective of the simulation model is to assess the effect of the suggested scenarios mentioned in section 6.3. Each scenario is judged by its respective total cost, efficiency and pick rate compared to the established practice. Furthermore, the model properties are as follows: The model should

- represent the order pick processes in the fast-pick and reserve areas of MKI warehouse.
- simulate the order pick process and provide at least the total cost of each scenario.
- consider singularities that significantly affect the order pick performance such as the number of picks, pick time or capacity of tow tractor.
- be able to process historical and random pick task data from a representative and significant period of time.
- be an exact representation of the warehouse dimensions and its storage locations.

7.3.2 Model framework

This section describes the model framework illustrated in Figure 7.1. The model framework can be divided into three categories: input of the model, the model itself and output of the model. Each category is elaborated in detail.

7.3.3 Model input

This section delineates the input parameters of the simulation model.

1. **SKUs**: A list of SKUs obtained from the assignment strategy is assigned to the bins in the fast-pick area in the model.
2. **Historical pick tasks**: Pick tasks are one of the main inputs to the simulation model. The storage location of each SKU is known and is indicated by the bin names, e.g. $AF001 - 0150$. The storage bin location code is defined as "{two letters indicating aisle : AF} {three digit indicating the rack number: 001} - {two digit bin section number: 01} {two digit level number: 50}". It must be noted that when SKUs have to be assigned to different bins from the current ones, the input list of storage location changes and not the simulation model itself.
3. **Distributions of SKUs**: Hourly arrival rate of each SKU is determined and used to generate pick tasks at 06:00, 08:00 12:00 and 18:00 during the day. Poisson distribution suited the best for the arrival process. The lamda values are taken as input into the model.
4. **X,Y,Z co-ordinates**: All the shelves, bins, conveyors and home locations of resources are represented by X,Y and Z co-ordinates. However, the routes for the pickers and reachers are designed by inserting walls around the racks based on the CAD diagram of the MKI warehouse.

5. **Travel speed in fast-pick area,** m/s: In order to create a representative output, the model uses the real travel speed of the order pickers. After observation of the picking process, it seemed fit to use a triangular distribution of ($minimum = 0.5$, $maximum = 1.0$, $mode = 0.7$).

6. **Pick time in fast-pick area,** s: Similar to the travel speed, the picking time is sampled using a triangular distribution of ($minimum = 9$, $maximum = 20$, $mode = 13$). This time includes the time taken to scan the bar-code, pick the product from the bin and place it on the conveyor.

7. **Travel speed of order picker in reserve area,** m/s: To produce output that represents reality, actual dimensions of the MKI warehouse is used. As a result, distances between storage locations are calculated by Anylogic and subsequently the corresponding travel times are used by the resources. Since the picker in the reserve area uses a tractor with roll cages, the speed is set to 0.8 m/s and the turn radius is set to 1.5 m/s.

8. **Pick time in reserve area,** s: The pick time in the reserve area consists of a loading time and an unloading time. Loading of an item includes the activities: searching for the bin, scanning, picking and placing in the roll cage. Again, a triangular distribution with parameters ($minimum = 20$, $maximum = 35$, $mode = 24$)is used for loading time (in seconds). The unloading time is the time taken by a picker to pick the product from the roll cage, place it on the conveyor belt and handling of roll cage. Unloading time (seconds) uses a triangular distribution of ($minimum = 3$, $maximum = 5$, $mode = 4$).

9. **Reserve area pick capacity**: Order pickers in the reserve area use roll cages to collect orders. Since, the SKUs are of varying size, the capacity of the an order picker is set to uniform distribution of ($minimum = 50$, $maximum = 75$) based on the observations and maneuverability of the tractor.

10. **Reacher speed and replenishment time**: The travel speed of the forklift is set to 2 m/s. The time spent to fetch a pallet from its source bin is modeled from a triangular distribution ($minimum = 3$, $maximum = 5$, $mode = 4$). The time spent in placing the fetched pallet in the destination bin uses the same triangular distribution. The traversal speed of the forklift to reach the height of rack level is 1 m/s.

11. **Cost**: Picker and reacher costs are set to 18 € and 22 € per hour, respectively.

12. **Replenishment threshold**: The threshold to trigger a replenishment task is set as follows. As soon as the count of items in a bin reaches this threshold, a replenishment task is triggered.

    - Old design bin in fast-pick area: 60% of pallet norm
    - New design (split) bin in fast-pick area: 60% of $\frac{\text{pallet norm}}{2}$
    - Bin in reserve area: 0

13. **Replenishment probability**: Usually, the fast-pick area (4500) is replenished from section 1500 in reserve area and 3500 from section 1510. However, this occurs around 90% of the times. The other ten percent of times, 4500 is replenished from 1510 and 3500 from 1500. To represent the reality of the MKI warehouse, the replenishment

probability is given as input to the model, so that the users may alter this variable as per requirement.

14. **Resource capacity**: Number of pickers and reachers required are as defined by parameters n_{pf}, n_{pr} and n_r.

15. **Work schedule**: The reachers work at different times, usually just until the picking tasks are released. The working schedule is tabulated in Table 7.1.

Table 7.1: Resource schedule

Resource ↓, Hour →	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Order Pickers	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reachers	✓	×	×	✓	×	×	✓	×	×	×	✓	×	×	×	×	✓	✓	✓	✓
Pick release	×	✓	×	×	✓	×	×	×	✓	×	×	×	×	×	✓	×	×	×	×

7.3.4 Model structure

The simulation model consists of static elements (infrastructure) based on the layout shown in Figure B.1. The layout represents the walls and shelves, setting a guideline for the picker and reacher movements. The bin configuration takes the input from the database consisting of the x, y and z coordinates and sets up the bins in the model. The population (dynamic elements) and the processes (events) are conceptually represented in Figure 7.2.

The simulation flow consists of the following steps:

1. A source object introduces picking tasks, controlled by an arrival schedule mimicking the real arrivals.

2. Picker is selected and allocated to a task, and the simulation of their movement begins with a delay object (acceleration).

3. The picker moves to the picking position. Movements that are controlled by the aforementioned network associated with the model.

4. After moving, a delay object accounts for the deceleration of the picker. The existence of separate delays representing acceleration and deceleration ensures that simulation of movement is realistic.

5. After decelerating, picking takes place and, if the picking list continues, the model becomes iterative.

6. The stock count of the picked product is decremented after every pick, and a decision object evaluates if a replenishment task must be triggered. A replenishment task consists of a random source storage bin in the reserve area and the corresponding picking bin as the destination storage bin.

7. Subsequently, the picker moves to the next closest picking location else returns to the home location.

8. After moving to the home location, the picker is released The picker waits for the arrival of the next set of picking tasks and follows steps 2 through 7.

9. Reachers have a schedule and once their schedule starts each reacher is assigned a replenishment task.

10. A reacher travels to the high-rack area and retrieves the product for a specific time introduced by a delay function.

11. After retrieval, the reacher travels to the storage bin for replenishment following the network of the model. Again, the reachers are configured with acceleration, deceleration and speed parameters.

12. A delay function determines the time taken by the reacher to store the product in the storage bin.

13. The model iterates through the steps 2 through 12 to complete the replenishment tasks in a FIFO manner.

Respecting the framework in the Figure 7.2, the picker flow block has an iterative nature to guarantee that pickers keep picking until all the picking tasks in the queue are completed. Similarly, the reacher flow block is also iterative to ensure completion of all replenishment tasks. By observation in the warehouse, it was decided to use triangular distribution for the delays and duration of events in the model, as given in section 7.3.3.

7.3.5 Model output

The following metrics which include the warehouse costs are monitored during the simulation.

- Warehouse cost per pick task (WPP)
- Number of picks per labour hour (PPH)
- Total material handling cost (TC) = Cost of put-away + Cost of internal replenishment + Cost of order-picking = 2× Cost for internal replenishment + Cost of order-picking ($\because$ time taken for replenishent = time taken for putaway)
- Individual costs per picking and replenishment in forward and and reserve areas
- Cycle time of pick and replenishment tasks (CT)

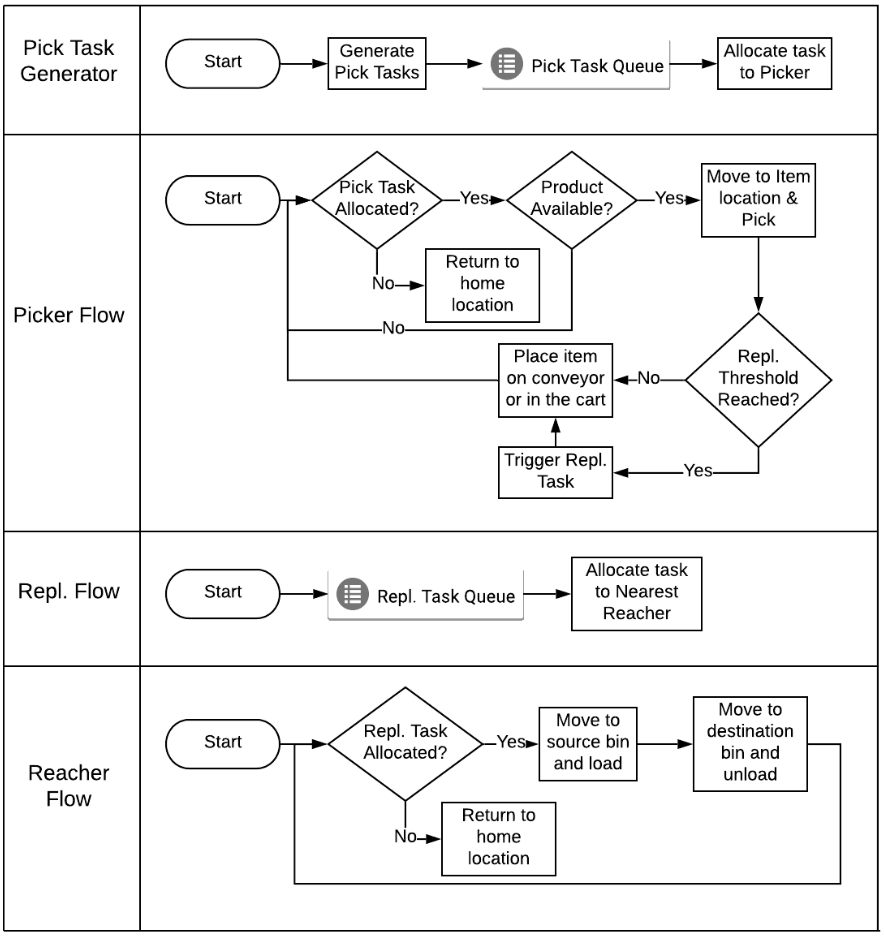


Figure 7.2: Simulation Flow Diagram

7.4 Model validation and model verification

Verification and validation are essential phases of the model development process. Verification refers to the steps, processes or techniques that are employed in the model to ensure the model behaves according to every initial specification. Validation ensures that the model adequately represents and reproduces the behaviours of the real-world phenomenon (North & Macal 2007).

7.4.1 Verification

In this research, the verification of the model embraced several steps and tests that were performed repeatedly throughout the development of the model.

- **Stress testing**: Each component of the model and the model itself were tested under extreme or unlikely situations such as zero-speed, zero-agents, simultaneous pick requests, ever-growing demand and capacity. In such situations, the flaws and errors are easily detectable.

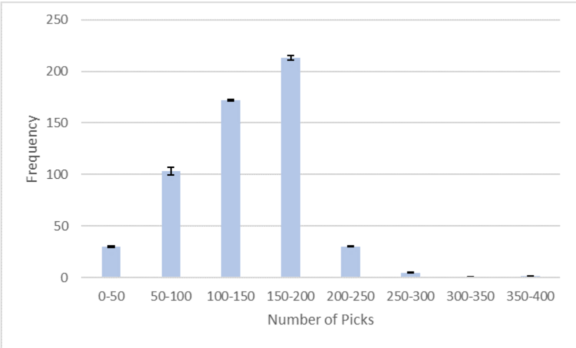
- **Debugging**: AnyLogic facilitates debug function to rectify the syntactic errors.
- **Stage by stage**: The model was built piece by piece, and every new feature or improvement was introduced only after being subjected to a complete set of tests. The object-oriented nature of JAVA programming in AnyLogic enables the insertion of new objects without the need to modify the rest of the model. Replications of simulation runs were conducted to check for errors and increase the transparency of the model.
- **Animation**: AnyLogic supports 3D animation and test runs coupled with inspection of running statistics were conducted to observe the the model's flow.

7.4.2 Validation

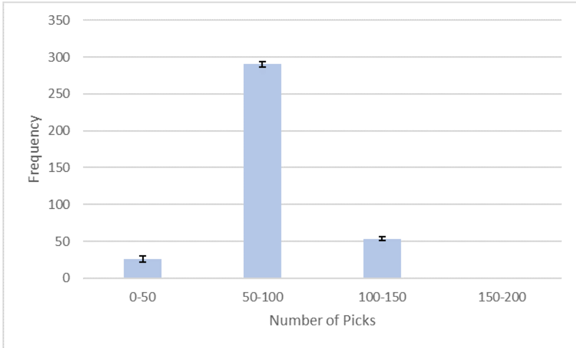
In addition to verification, the model was subjected to validation. Validation ensures that the model adequately represents reality at MKI warehouse and that the outputs are meaningful. The validation included interviews and comparison of outcomes between the model and data analysis presented in section 4.1.The process of validation is meant to ensure that the model adequately represents the real world and that its outcomes are meaningful. There are several techniques for validation; the one adopted in this project is based on the work of North & Macal (2007) and involves the following steps:

- **Requirements Validation**: *(The model should meet the requirements and exhibit real-world situations.)* The model simulates the conventional strategies and processes of MKI warehouse.
- **Data validation**: *The data used in the model should be valid.* The model uses historical pick tasks from SAP EWM tool.
- **Face Validation**: *(The assumptions of the model should be valid.)* Every assumption of the model is either based on literature references or discussed with the stakeholders. The model is validated with the two company supervisors. There were a couple of meetings where the model was shown. The model is adapted to the comments given in these meetings.
- **Process Validation**: *(Resources and their interactions' structure and steps in the model have to be clear, meaningful and correspond to real-world process.)* The structure of the simulation model replicates the process of the warehouse. Furthermore, the structure was developed with consultation from the Supply Chain Control team.
- **Theory Validation**: *(Model's theories have to be valid and used correctly.)* The properties of the functions and the model environment are based on sound theoretical formulations, e.g., replenishment trigger function.

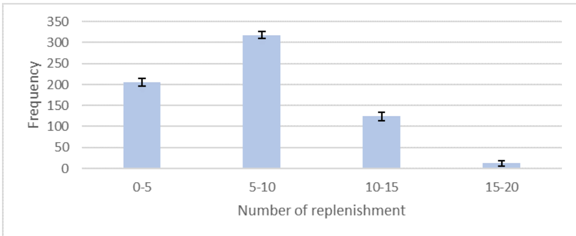
The model is initially validated with six months of historical data. Further, the historical data is fit with Poisson distribution based on the pick tasks released every hour. The main objective behind fitting a distribution is to capture the pick tasks generated in specific intervals and eliminate the effect of seasonality on the arrivals. The simulation model with Poisson arrivals is simulated for one month and replicated ten times with random seeds. The resulting plots for the pick rates are shown in plots 7.3a and 7.3b. Comparing these two plots with the plots obtained from data analysis, Figure 4.6, it can be inferred that the picking rate is captured adequately in the simulation model. Similarly, the replenishment rate can also be confirmed from Figure 7.3c. The graphs presented in Figure 7.3 include 95% confidence intervals (shown as black lines).



(a) Pick rate - Fast pick area



(b) Pick rate - Reserve area



(c) Replenishment rate

Figure 7.3: Simulation results

7.5 Model run time

Each simulation run with input as arrival rates are replicated ten times with random seeds. Since long-term statistics are of interest in this research and the simulation starts with a fully stored warehouse, the statistics collection is started after an initial period of five days (*warm-up period*) to avoid the biasing effect of the initial conditions. The length of warm-up period is determined by inspecting the plot of resource utilization plot against time (seconds), shown in Figure 7.4. Each replication length is set to two months.

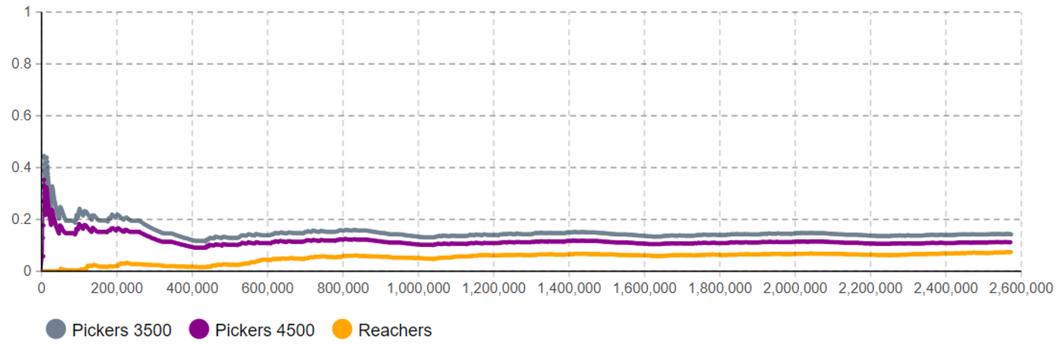


Figure 7.4: Utilization vs. time plot

7.6 Summary

This chapter explained the simulation model that has been used to test each scenario of Chapter 6. Firstly, the model objectives, where the main goal of the simulation model is to assess the effect of the suggested order pick scenarios on the pick line productivity. Subsequently, the model assumptions and framework are elaborated. Finally, the procedure that is used to verify and validate the simulation model is showed. Verification and validation are essential phases of the model development process and therefore are explained in detail.

Chapter 8

Results

The results obtained from the simulation model that is used to determine the effect of the developed scenarios are reported in this chapter. The objective of the experimentation phase is two-fold:

1. Determine the system capacity in terms of number of pickers and reachers required to satisfy the regular daily demand.

2. With the available workforce, identify a reasonable storage strategy (optimal number of bins, assignment and allocation) and again, determine the capacity of the workforce.

These analyses are reported in sections 8.1 through 8.3. Further, results obtained from updating the picking route sequence for reserve area is presented in section 8.4. This chapter is concluded with a sensitivity analysis in section 8.5.

8.1 Workforce capacity

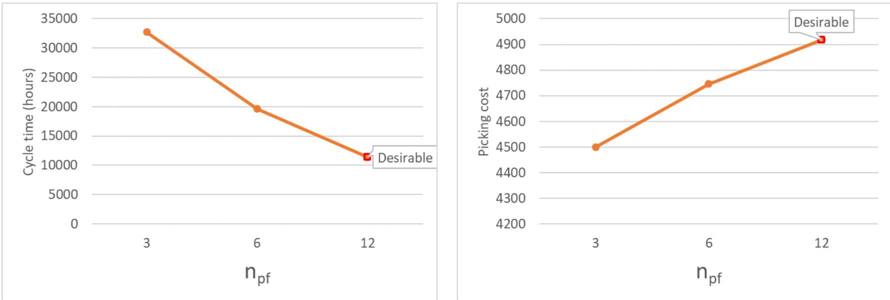
With the current set of 828 SKUs allotted in the fast-pick area (4500) and the remaining 828 SKUs present in the reserve area (3500), the following parameters are varied to obtain 105 scenarios.

- Number of pickers in fast-pick area: $n_{pf} = 3, 6, 12 \implies$ {1,2,4} number of order pickers per floor

- Number of pickers in reserve area: $n_{pr} = 1, 2, 3, 4, 5$

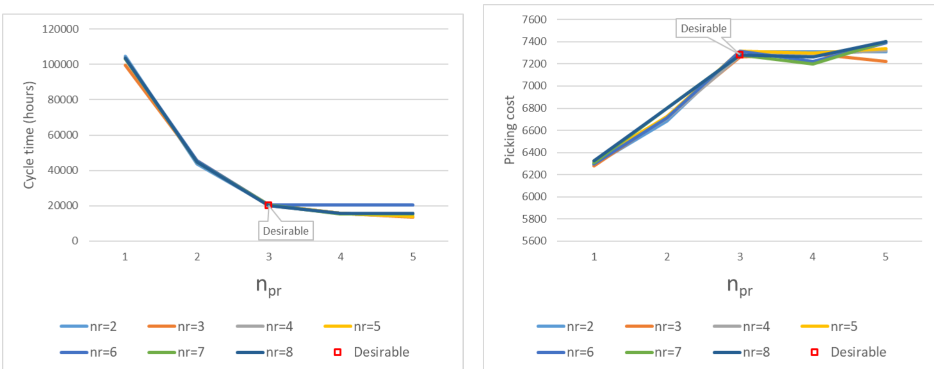
- Number of reachers: $n_r = 2, 3, 4, 5, 6, 7, 8$

Total cycle time (CT) and cost of the tasks are the criteria used to choose a reasonable set of workforce. Cycle time of pick tasks is calculated as: (Time when an item is placed on the conveyor - Arrival time of item request). Similarly, the cycle time of replenishment tasks is: (Completion time of replenishment - Trigger time of replenishment task). The results from the workforce parameter variation is shown in Figures 8.1 through 8.3, where the average CT and the average costs are plotted for each scenario. The performances of the resources have dependency on each other. For example: if there are more number of pickers, the sooner the picks occur which in turn trigger replenishment earlier in the day. The following observations are made to decide the set of workforce.



(a) Cycle time - Forward area (b) Picking cost - Forward area

Figure 8.1: n_{pf} capacity variation



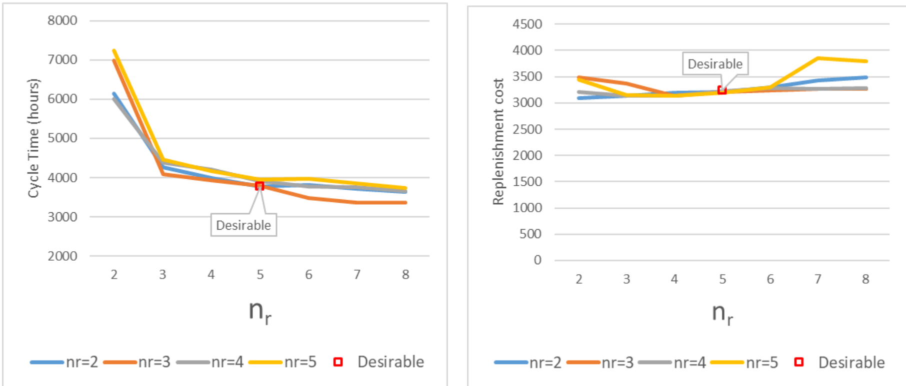
(a) Cycle time - Reserve area (b) Picking cost - Reserve area

Figure 8.2: n_{pr} capacity variation

- Number of order pickers in fast-pick area is varied based on the sectioning of the warehouse. The cycle time, as shown in Figure 8.1a, improves significantly when the number of pickers is increased from three to six, but, additional costs incur. However, when 12 pickers are used in the fast-pick area, CT decreases while the cost increases slightly. Thus, with little increase in the cost, 12 pickers can be accommodated to have an improved CT. This behaviour is observed for all the combinations of n_r and n_{pr}.

- In the case of order pickers in the reserve area, CT reduces greatly when n_{pr} is increased from 1 to 3. However, there is a significant increase in picking cost (Figure 8.2b). For instances with higher number of reachers, slightly higher costs are seen. This occurs due to the congestion of reachers and order pickers traveling in the reserve area. Since no significant decrease in the travel time is seen for $n_{pr} > 3$, 3 pickers are considered for further evaluation.

- A gradual decrease in the CT of replenishment tasks is seen in Figure 8.3a. As the number of reachers increase, the cost increases slightly. However, the choice of n_r is made such that the congestion in the reserve area is at its least. Thus, the number of reachers is set at 5.



(a) Cycle time - Replenishment (b) Replenishment cost

Figure 8.3: n_r capacity variation

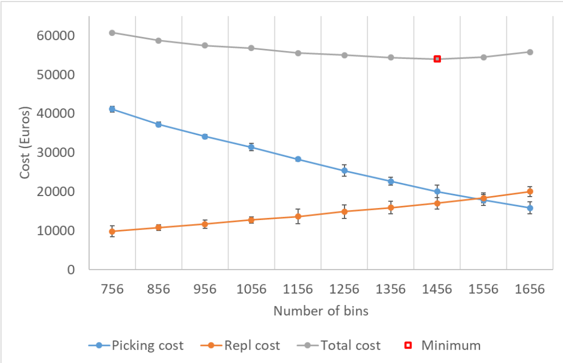
For further evaluation of assignment and allocation strategies, the set of workforce is: $\{n_{pf}, n_{pr}, n_r\} = \{12, 3, 5\}$.

8.2 Assignment and allocation

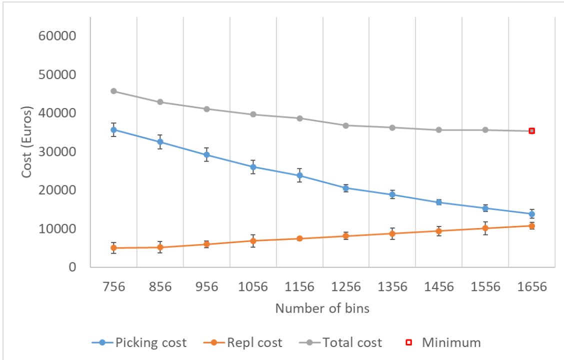
The number of bins (n_{bin}) in the fast-pick area is varied (828 to 1656) to identify the reasonable number of SKUs that can be assigned to the forward area. To form a baseline for analysis, the SKU set from current assignment method is simulated. The SKUs obtained from the EAQ and LE methods are adopted in the model for bin variation. The number of bins are varied in multiples of 100. The simulation scenarios use the optimal workforce obtained in section 8.1.

The results obtained after allocation in the simulation are plotted in Figure 8.4. Under all the three assignment methods, as the number of bins increases, the cost of picking decreases significantly, but the cost of replenishment increases slightly. The current method yields the highest total costs compared to the other two methods. Since, the current method does not consider the pallet norm during the assignment of SKUs, it causes a high replenishment cost even with lesser number of bins, as shown in Figure 8.4a. The EAQ method yields a lower replenishment cost in the beginning, however, the replenishment cost surges with increase in the number of bins. The EAQ strategy outperforms the two methods in both picking and replenishment costs. However, on a closer look, this method yields the least number of picks in the forward area as reported in Table 8.1. EAQ method, essentially, could lead to lesser number of picks in the long-term. This could lead to under-utilization of the fast-pick area which is undesirable.

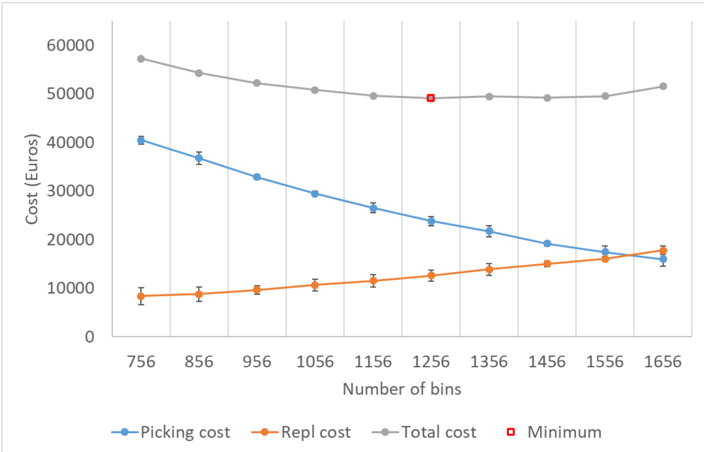
The total material handling costs (TC = 2 × replenishment cost + picking cost) are also plotted for each method in Figure 8.4. Again, EAQ outperforms both the methods and has a minimum at $n_{bin} = 1656$. LE method is the next best method which considerably decreases the total cost on addition of every 100 bins. The minimum total cost is found at $n_{bin} = 1256$. The current method yields the highest total costs and has a minimum at $n_{bin} = 1456$. The selection made by the labour efficiency (LE) method, yields more picks as well as a reasonable saving in total costs (Figure 8.5a). The EAQ and LE method show a



(a) Current method



(b) EAQ method



(c) LE method

Figure 8.4: Costs vs. n_{bin}

significant saving in all the bin variation scenarios as shown in Figure 8.5b. Additionally, as discussed in section 6.4, the set of SKUs obtained from LE is selected as the best performing policy for further evaluation. With $n_{bin} = 1256$, the costs and number of picks obtained are reported in Table 8.2. Although, EAQ amounts to higher savings, the LE method gives a high number of picks with lesser number of bins. Since, splitting the bins results in additional infrastructure costs, it would be beneficial to have high number of picks with least number of bins.

8.2.1 Efficiency measurement

The warehouse cost per pick (WPP) and number of picks per hour in the fast-pick area (PPH) for the three methods are plotted in Figure 8.6. WPP is given by equation 8.1.

$$WPP = \frac{\text{(picking + replenishment + put-away costs) from reserve and forward areas}}{\text{Total number of picks from reserve and forward areas}} \tag{8.1}$$

Table 8.1: Average number of picks in the forward area during the simulation period.

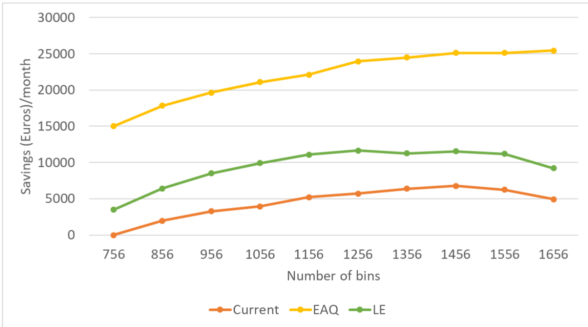
Method→ / n_{bin} ↓	Average number of picks from the fast-pick area		
	Current	EAQ	LE
756	123758	107242	127577
856	133206	115340	138117
956	140657	123282	146338
1056	147312	130182	154431
1156	154799	137751	160524
1256	161894	144291	167370
1356	168399	148435	174001
1456	174736	153188	178686
1556	180077	156819	183388
1656	184873	161397	186498

Table 8.2: Average cost and number of picks for $n_{bin} = 1256$

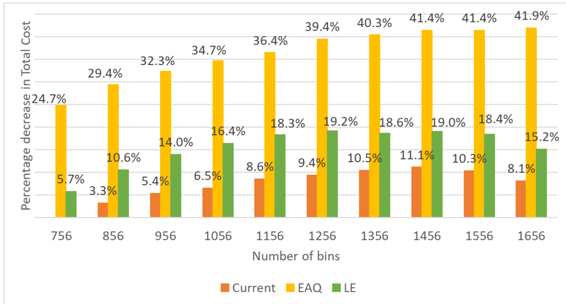
Method	Total Cost	No. of picks in forward area
Current	55013.4	161894
EAQ	36799.1	144291
LE	49077	167370

It can be observed from Figure 8.6a that the current method yields a high WPP in all the scenarios due to the high number of replenishment costs. EAQ and LE methods show a substantially lesser WPP. On an average, the current storage assignment method amounts to 30.45 cents per pick while EAQ and LE yield 24.11 and 27.45 cents per pick respectively. EAQ and LE policies improve WPP by 20.8% and 9.8% respectively. This indicates that the selection of SKUs made through the new assignment methods shows an improvement in the efficiency.

The LE method outperforms the other two methods when PPH is taken into consideration. The selection of SKUs made through the current and EAQ methods do not generate enough picks to reach a maximum PPH. In LE method, the PPH increases significantly until $n_{bin} = 1256$ and doesn't show much improvement than that. This behaviour can also be seen in the total costs obtained by the LE assignment method (Figure 8.4c). Hence, $n_{bin} = 1256$ can be considered as a reasonable number of bins that should be present in the fast-pick area. After discussion with the stakeholders from the supply chain team, it is decided to evaluate the policy around the suggested n_{bin} value. LE policy is further evaluated by varying the number of bins between 1156 and 1356 to determine a set of bins and workforce that yield a reasonable total cost.

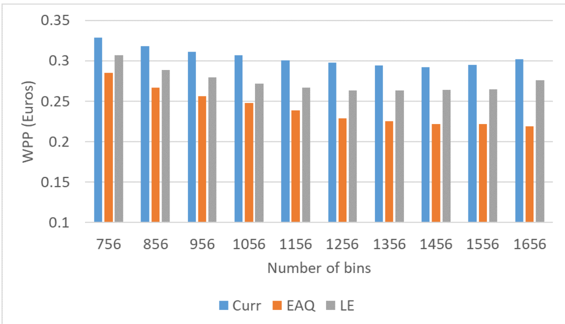


(a) Savings per month

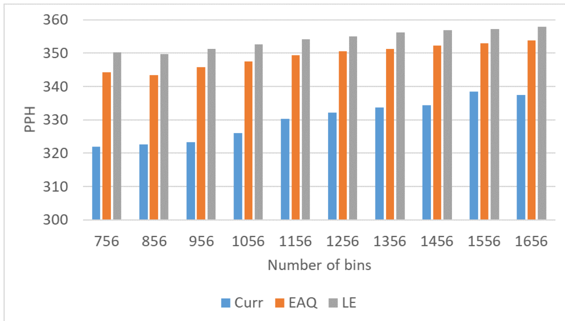


(b) Percentage decrease in total costs

Figure 8.5: Savings under the assignment methods for varying n_{bin}



(a) Warehouse cost per pick



(b) Pick rate

Figure 8.6: Performance vs. n_{bin}

8.3 Labour efficiency and optimal workforce

To determine the optimal number of bins required in the fast-pick area, parameter n_{bin} is varied between 1156 and 1356 in multiples of 20, shown in Figure 8.7. The minimum total cost is found at $n_{bin} = 1236$. The slopes of the picking and replenishment costs are not steep, and, the total cost also does not vary much. Thus, it can be inferred that the selection of n_{bin} in the domain [1216,1256] would be beneficial.

The SKUs selected by the labour efficiency method are employed in the simulation model and the parameters, n_{pf}, n_{pr} and n_r, are varied, while keeping $n_{bin} = 1236$. This analysis is carried out as a part of sensitivity analysis. Some of the significant observations made during the analyses are as follows:

- Irrespective of n_{bin}, n_{pr} and n_r, setting number of order pickers in the fast-pick area to $n_{pf} \in \{3, 6, 9\}$, increases the cycle time of the picking in fast-pick area largely. This is undesirable and thus, n_{pf} is kept at 12.

- Similarly, irrespective of other parameters, the parameter n_r showed the following behavior which is similar to that shown in Figure 8.3a. Adding reacher capacity decreases the replenishment time and thereby the total cost.

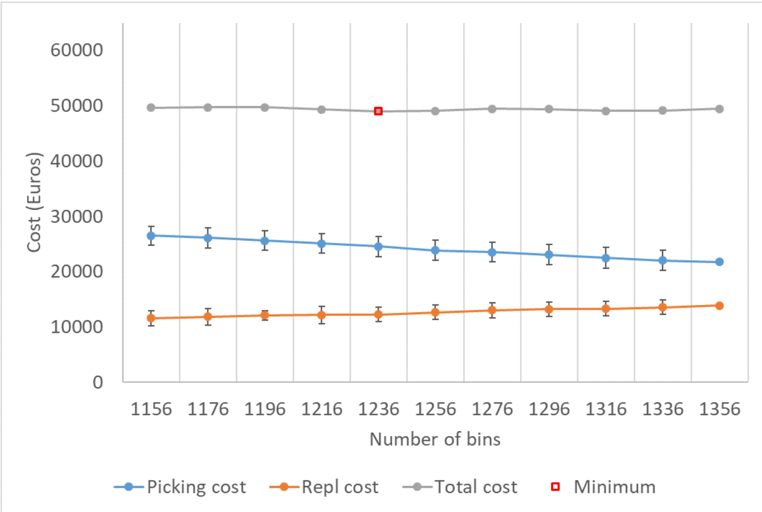


Figure 8.7: Labour efficiency: Bin variation results

  - For $n_r \leq 5$, the cycle time of replenishments increases largely, but the replenishment cost decreases.
  - For $n_r \geq 7$, the cycle time decreases, however, the replenishment costs increase.
  - For $n_r = 6$, both the cycle time and the costs are found to be satisfactory.

- Number of pickers required in the reserve area (n_{pr}) depends on the number of bins in the fast-pick area (n_{bin}). As n_{bin} increases, the pick tasks generated in the reserve area decreases, thus, the requirement for pickers in the reserve area decreases. However, due to the single-sided picking sequence, two pickers in the reserve area are still required.

8.4 Picking route 3500

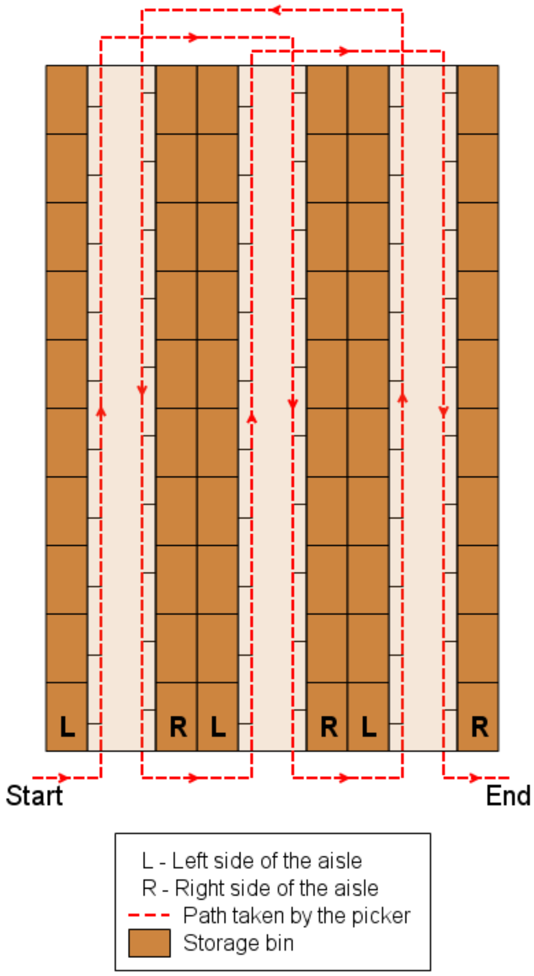
Figure 8.8a shows the current sequence of route set for picking in the reserve area. Due to the presence of the walls at the end of the halls, different routing sequences didn't improve the travel distance. One of the routing sequences that gave a closer result is looping around the each rack. However, the current method, proved to be the best possible sequence.

Two alternatives to this problem are:

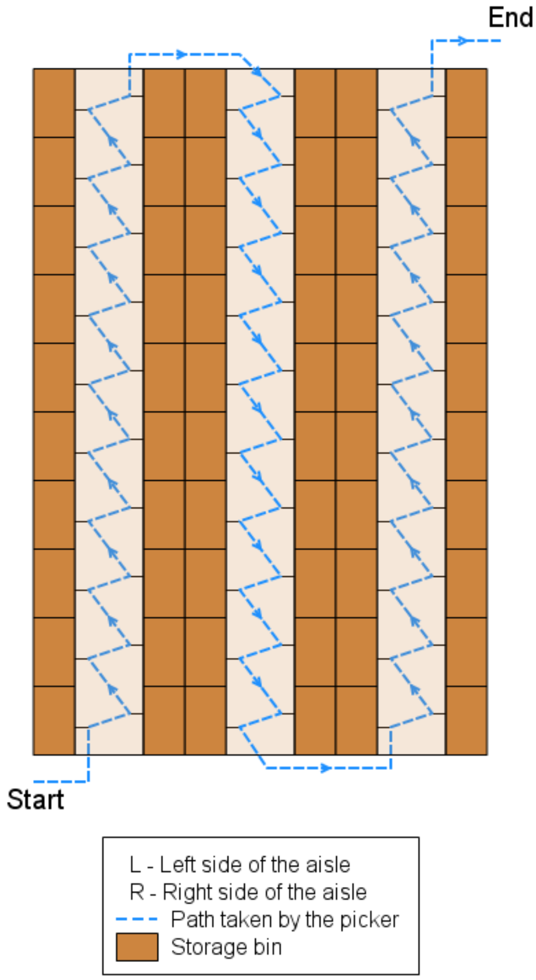
1. Replace the single-sided roll cages with a double-sided picking cage.

2. Attach single-sided roll cages alternatively such that few are open on the left and few on the right.

With the suggested alternatives, a conventional S-shaped aisle-by-aisle route can be followed as shown in Figure 8.8b with the same pick capacity. With $n_r = 5$ and $n_{pf} = 12$, n_{bin} and n_{pr} are varied to evaluate travel cost incurred by single-sided and double-sided picking. The results (with 95% C.I.), i.e. time taken for picking through both picking sequences and the percentage decrease are plotted in Figure 8.9. The total picking time decreases by, on an average, 36% in all the scenarios. Consequently, the decrease in the reserve area substantially shifts the minimum point of total costs towards left leading to lesser number of bins in



(a) One-sided picking route



(b) Two-sided picking route

Figure 8.8: Picking route sequence

the fast-pick area. Figure 8.10 illustrates the costs obtained by employing single-sided and double-sided picking sequences.

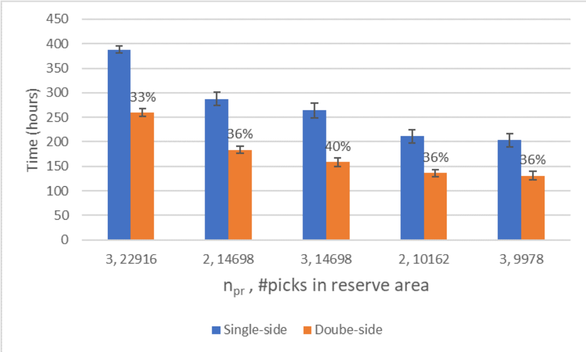
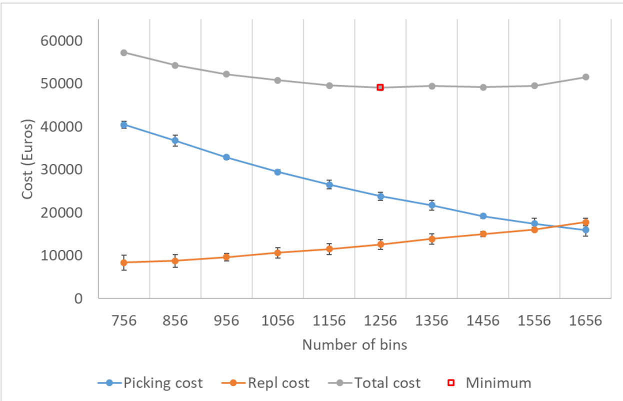
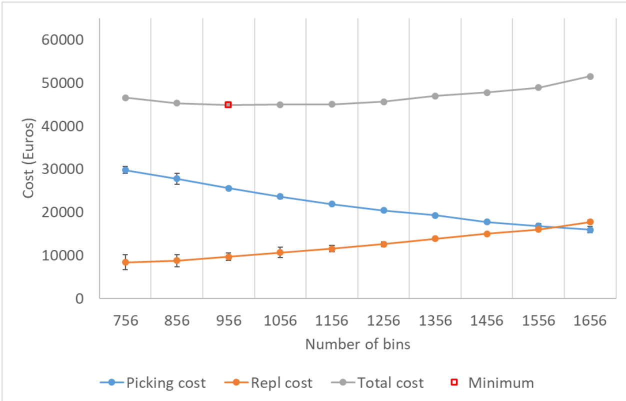


Figure 8.9: Total picking time in reserve area for single and double sided sequence



(a) One-sided picking



(b) Two-sided picking

Figure 8.10: Bin variation output of LE method with different picking methods in reserve area

8.5 Sensitivity analysis

This section checks the robustness of the model to establish the reliability and applicability of the results. The following factors are varied and the response of the picking and replenishment costs are analyzed.

8.5.1 Time parameters

The following observations are made when the speed of the resources and the time taken for picking and replenishment activities are varied.

1. Number of picks per hour (PPH) is directly proportional to the speed of the workers. The faster the pickers move, the lesser time they consume to carry out the activity. In turn, the number of picks carried out increases. However, if the worker speed is decreased, PPH decreases proportionally. On the contrary, warehouse cost per pick (WPP) is indirectly proportional to the speed of the workers, i.e. higher worker speed leads to lesser WPP.

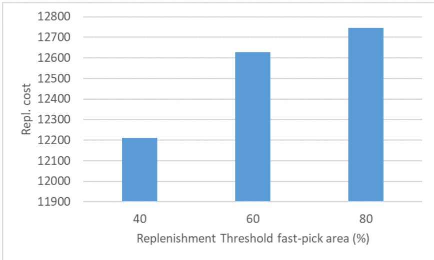


Figure 8.11: Replenishment: Cost vs. threshold

2. PPH is indirectly proportional to the picking time while WPP is directly proportional to the picking time. The more the time consumed for picking, the lesser PPH and higher WPP. Similar behaviour is observed in case of replenishment (loading and unloading) times.

Picking time highly influences the number of storage bins in the fast-pick area. The relations presented in Table 8.3 hold for all the three assignment methods. The third relation can be observed in Figure 8.10, where the number of bins in fast-pick area decreased when the picking time in reserve area decreased.

Table 8.3: Pick time influence on n_{bin}

Pick time in fast-pick area	Pick time in reserve area	n_{bin}
↑	–	↓
↓	–	↑
–	↑	↑
–	↓	↓

Notes: ↓ decrease in picking time; ↑ increase in picking time; – no change in picking time.

8.5.2 Replenishment threshold

The replenishment threshold is a parameter that effectively influences the replenishment cost in the warehouse. If the threshold is increased, the replenishment tasks are triggered sooner because replenishment task is triggered when the remaining items in the bin reaches the threshold level. During the period of simulation, the number of replenishment tasks and in turn the costs increase, when the the threshold is increased.

8.5.3 Resource cost

The cost of resources plays an important role in determining the number of bins required in the fast-pick area. Unlike the picking time, the influence of the picking cost on n_{bin} is not straightforward. Since, the order pickers in both fast-pick and reserve areas are paid the same wages, the number of bins depends on the number of picks carried out in these areas. The hourly costs of pickers (XP) and reachers (XR) are varied in steps of 0.5 and significant results are reported in table 8.4. In all the scenarios, increase in reacher cost leads to decrease in n_{bin}. This is as expected because the number of replenishments in the fast-pick area increases with increase in n_{bin}. On the contrary, if the picker cost is increased, n_{bin} increases. As the total picking cost in the reserve area increases, it is best to shift the products to the fast-pick area and thus, have higher n_{bin}.

Table 8.4: Influence of resource cost on n_{bin}

HPC ↓ , HRC →	$XR-2$	XR	$XR+2$	$XR+4$	$XR+6$
$XP-1$	1456	1256	1256	1256	1156
XP	1456	1256	1256	1256	1156
$XP+1$	1456	1456	1256	1256	1256
$XP+4$	1556	1556	1456	1456	1256
$XP+6$	1556	1556	1556	1456	1456

Notes: HRC: Hourly reacher cost; HPC: Hourly picker cost; Costs are anonymized for confidentiality reasons.

8.6 Summary

In Chapter 6, assignment methods were discussed, which could potentially result in an improved pick efficiency. To evaluate the methods, various scenarios were simulated, and this chapter analyzed the outcomes by using many KPIs.

As a result, it can be concluded that almost all scenarios potentially result in lesser costs with sufficient workforce capacity. Therefore, it can be inferred that all scenarios are expected to result in improvement. The sensitivity analyses presented in this chapter confirmed most of the hypotheses discussed with the company and also shows that the results of the main case study are robust. Even with a change to the static element (picking route in the reserve area), the model still performed as expected and suggested the required improvement.

Chapter 9

Conclusion and recommendations

9.1 Conclusion and discussion

As presented in Chapter 8, the allocation strategy shows the decrease of total material handling cost, by implementing the proposed methods. The total cost decreases as the SKUs are shifted from reserve area to the forward area, in this design. Besides the allocation strategy, this research discovers that the right assignment of SKUs to the fast-pick area will also lead to a decrease in the total cost and thereby also improve the pick efficiency. The research questions are answered in section 9.2, by summing up the findings within this research. The limitations of this research and the opportunities of further research are presented in the following sections.

9.2 Reflection

This research started with a main research question and five sub-questions. This section will reflect on these questions. First, the sub questions will be addressed and finally, the main question will be answered.

What are the KPIs used by vidaXL to assess the performance of processes involving conveyable items? What is the current performance in relation to the selected KPIs?

The KPIs found relevant to this research are presented in section 4.1. The KPIs were analyzed based on the reports from the SAP tool and the current performance was evaluated. Picking percentage mainly indicated that there is room for improvement and thereby paved way to identify bottlenecks. However, the current KPIs were found to insufficient to address the research problem. Thus, additional KPIs such as movement cost (cost for picking and reach movements) and warehouse cost per pick (WPP) were introduced along with a number of design parameters. The approach culminated in a savings based analysis.

What are the bottlenecks that significantly affect the KPIs?

The bottlenecks identified in the warehouse are detailed in section 4.2.1. The summary is as follows:

- Assignment of products to the fast-pick area: Current method of assignment selects the SKUs based solely on the monthly average demand. This method attributes to higher replenishment costs since lesser pallet norm (quantity of an SKU that can go on a pallet) can lead to more number of replenishments.

- Storage design in the fast-pick area: The double-deep bins in the forward area allocate two pallets of one SKU. However, there is a provision to split these bins to accommodate two half pallets of two SKUs. Current storage bin design hinders allocation of more SKUs to the fast-pick area.

- Allocation of bins to the products in the fast-pick area: An equal space allocation is in place, i.e., two-pallets of each product is stored in a bin. However, the allocation can be varied to reduce picking costs by accommodating more SKUs in the fast-pick area or reduce replenishment costs by giving more bin space to certain SKUs.

- Picking sequence in the reserve area: Due to the use of tow tractor with single-sided roll cages for picking in the reserve area, every aisle is visited twice to pick from left and right. Furthermore, the turn radius of the tow tractor disallows turning in the middle of an aisle. This potentially increases the travel time of the picker and thus, increasing the picking costs.

What are the design parameters and policies that can be changed to improve the KPIs given the limitations of the warehouse design and SAP EWM compatibility?

The feasibility of changing the design parameters is checked with the supply chain control team. The design parameters used in evaluation of different strategies are explained in section 6.2.

What are the design parameters and policies related to a storage area that can be changed?
Number of bins in the fast-pick area is the key parameter that can be changed. This design change makes it possible to accommodate more SKUs to the fast-pick area than there is currently. The storage policies are based on two decisions, assignment (which SKUs to assign to the fast-pick area) and allocation (quantity of these SKUs to allocate). Along with the current assignment method, Economic Assignment Quotient (EAQ) and Labour Efficiency (LE) were evaluated to obtain the assortment of products for fast-pick area. This change is found to be feasible for execution in SAP.

How can picking efficiency be increased by integrating the new storage policy?
The picking efficiency in this research is estimated in terms of warehouse cost per pick (WPP) and number of picks per hour (PPH). The EAQ and LE methods decrease WPP by 20.8% and 9.8% respectively. PPH increases from 322 to 349 in case of LE policy. In case of EAQ, PPH slightly increases to 330 because the number of picks yielded by EAQ is less, however, the selection of SKUs are such that highly ranked SKUs generate more pick tasks within an hour. Another measure used to determine the improvement based on activity based costing is the total material handling cost (sum of put-away, picking and replenishment costs). With current storage design where number of bins is 828, EAQ and LE show a saving of 42% and 49%, respectively, more than the current assignment method as shown in Figure 8.5. Based on company's motive, the following selections can be made.

- WPP: If the cost is the main priority, it is best suitable to choose EAQ as storage policy. However, the total number of picks generated by this method is less than that of other two policies.
- Total number of picks: If the aim is to pick as much as possible from the fast-pick area, then it is appropriate to choose LE which gives a hgiher PPH as well lesser cost compared to the current method.

How can the replenishment movements be minimized to maintain the picking efficiency?
The storage assignment methods, EAQ and LE, select SKUs based on the pallet norm, such that the number of picks is maximized while maintaining the number of replenishment at minimum. Adopting one of the proposed assignment methods, certainly leads to reduction in number of replenishment movements. Additionally, the following strategy, which would reduce put-away costs, is suggested to the company.

The “dock-to-forward” (DTF) technique is a strategy used in industry to reduce the additional handling due to replenishment. In this strategy, replenishment occurs directly from the receiving dock to the forward pick area for any SKU received and requires replenishment on the same day. Hollingsworth (2003) focused on minimizing replenishment costs through a DTF strategy and tested via simulation, where the best-performing DTF strategy reduced replenishment trips by 24% over a system with no DTF. vidaXL uses First In, First Out (FIFO) rule for managing inventory and does not make use of this strategy since the DTF technique bypasses reserve storage, i.e. a new pallet is moved to the fast-pick area before an old pallet that has been waiting in the high-rack. However, this technique can be applied at vidaXL with the following modifications.

- The system can check if the reserve area has a bin with the incoming SKU. If there exists a bin, the pallet is put-away to the high-rack area else to the fast-pick area.
- There is a possibility that the SKU is no more a fast-mover. Then, the system could check if there is a pick for the SKU on that day or has been picked in the last week and then load it onto the fast-pick area.
- If a partial pallet arrives, then the system could directly allocate it to the reserve area.

How do the proposed changes affect the KPIs?

The proposed changes give the following improvements in KPIs:

1. Fast-pick area bin design: The current bins in the fast-pick area can be split it two. This change consequently increases the pick rate and decreases WPP.
2. Storage assignment: Changing the assortment in the fast-pick area reduces WPP by increasing number of pick in the fast-pick area while keeping number of replenishment tasks as low as possible.
3. Storage allocation: Allocating bins based on the ranks than giving equal space to all the items, leads to more savings.
4. Picking route sequence in the reserve area: Substantial decrease in the travel time during picking can be seen and thereby a decrease in WPP.

5. Dock to Forward technique: This strategy essentially minimizes the number of reacher movements and also the total cost of the warehouse.

9.3 Theoretical contribution

This research culminated in a model that is able to allocate SKUs to the fast-pick and reserve area based on the storage strategies. During the literature review, it became clear that limited literature is available on forward-reserve problem. This research will complement the limited research on forward-reserve problems. This model demonstrated that the suggested methodologies (EAQ and LE storage strategies) in the relevant literature are indeed able to increase cost savings. However, the results also showed that storage assignment based on popularity (current method) does not result in savings compared to the other strategies. Furthermore, this research contributed to the research field of forward-reserve problem, by defining scenarios that can improve efficiency of warehouses that are faced with high number of picks and limited workforce.

9.4 Limitations

In this section, the limitations of the research are discussed.

- The model is only tested with the movement data of one company.
- The put-away movements are not designed but assumed as equal to replenishment movement in the simulation runs.
- The congestion within the aisles are directly solved by the simulation software and the additional time due to the congestion is not calculated.
- It is assumed that the reserve area has infinite capacity.
- It is assumed that during replenishment, there is no change of pallets required. This activity will add to the replenishment time and influence the results. However, the total picking time is the main contributor of the total cost and thus, there will be a saving by including this activity in this design.

9.5 Future research recommendations

Although this research provides a design which creates a case with less WPP, there are still aspects which require additional exploration.

- It was mentioned in the analysis of the current situation that many pallets are used in the MKI warehouse to utilize a storage bin completely. The use of different pallet types in the reserve area adds to the replenishment cost since the products placed in the fast-pick area uses only two types of pallets. Rather than looking for full utilization of a bin, it will be useful to investigate further whether all pallet types are required so that the replenishment costs reduces.

- It was suggested in section 9.2 that Dock-to-forward strategy may result in a significant improvement in the total cost. However, this is only concluded based on the logic setup in SAP EWM. It would be interesting to quantify this strategy and evaluate the extent to which this could be helpful.

- The picking locations in the reserve area (3500) use a closest-open bin strategy to assign products. However, it could prove beneficial to evaluate other storage assignment rules such as ABC classification in the reserve area.

- It would be interesting to test the model with different company's data and analyze the storage assignment rules.

- The inflow of the warehouse can be modelled to determine a waiting time of an order in the warehouse.

- Accounting for supply disruption is an interesting extension of this work (Atan & Snyder 2012b), (Atan & Snyder 2012a), (Atan & Snyder 2014), (Atan & Rousseau 2016).

9.6 Conclusion

This research aimed to answer the following question:

What improvements does vidaXL require for conveyable items with respect to storage, replenishment and picking processes to increase the warehouse efficiency given the limitations of the warehouse layout?

The results showed that all the suggested improvements (storage strategies, bin design, picking routes) lead to improvement in efficiency of warehouse, measured as WPP. Additionally, the outcomes of the simulations showed that vidaXL is able to potentially reduce the total material handling costs by approximately 19.2%. To accomplish this improvement, 428 bins in the fast-pick area need to be split to obtain a total of 1256 bins and LE method should be used for assignment. Moreover 39% reduction in costs can be seen if 1256 bins are allotted with SKUs from EAQ method, but this leads to decrease in number of picks. The assortment to be stored in these bins should follow LE assignment method. An alternative scenario, wherein the picking route in the reserve area is double-sided. The outcome from this scenario showed that the expected saving is at most 26% with 956 bins. These two scenarios can be applied with the same workforce capacity. Further recommendations are given to minimize the replenishment movements such as reducing types of pallets in the warehouse and application of DTF strategy.

Bibliography

Atan, Z. & Rousseau, M. (2016), 'Inventory optimization for perishables subject to supply disruptions', Optimization Letters **10**(1), 89–108.

Atan, Z. & Snyder, L. V. (2012a), 'Disruptions in one-warehouse multiple-retailer systems', Available at SSRN 2171214 .

Atan, Z. & Snyder, L. V. (2012b), Inventory strategies to manage supply disruptions, in 'Supply Chain Disruptions', Springer, pp. 115–139.

Atan, Z. & Snyder, L. V. (2014), Eoq models with supply disruptions, in 'Handbook of EOQ inventory problems', Springer, pp. 43–55.

Bartholdi III, J. J. & Hackman, S. T. (2008a), 'Allocating space in a forward pick area of a distribution center for small parts', IIE Transactions **40**(11), 1046–1053.

Bartholdi III, J. J. & Hackman, S. T. (2008b), Warehouse and distribution science, Supply Chain and Logistics Institute, School of Industrial and Systems .

Borshchev, A. (2013), The big book of simulation modeling: multimethod modeling with AnyLogic 6, AnyLogic North America Chicago.

Chan, F. T. & Chan, H. K. (2011), 'Improving the productivity of order picking of a manual-pick and multi-level rack distribution warehouse through the implementation of class-based storage', Expert systems with applications **38**(3), 2686–2700.

De Koster, R., Roodbergen, K. J. & Van Voorden, R. (1999), Reduction of walking time in the distribution center of de bijenkorf, in 'New trends in distribution logistics', Springer, pp. 215–234.

Dijkstra, E. W. (1959), 'A note on two problems in connexion with graphs', Numerische mathematik **1**(1), 269–271.

Faria, F. & Reis, V. (2015), An original simulation model to improve the order picking performance: Case study of an automated warehouse, in 'International Conference on Computational Logistics', Springer, pp. 689–703.

Frazele, E. & Sharp, G. P. (1989), 'Correlated assignment strategy can improve any order-picking operation', Industrial Engineering **21**(4), 33–37.

Frazelle, E. H., Hackman, S. T., Passy, U. & Platzman, L. K. (1994), The forward-reserve problem, John Wiley & Sons, Inc.

Gagliardi, J. P., Renaud, J. & Ruiz, A. (2007), A simulation model to improve warehouse operations, in 'Proceedings of the 39th conference on Winter simulation: 40 years! The best is yet to come', IEEE Press, pp. 2012–2018.

Goetschalckx, M. & Donald Ratliff, H. (1988), 'Order picking in an aisle', IIE transactions **20**(1), 53–62.

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

Gu, J., Goetschalckx, M. & McGinnis, L. F. (2010), 'Solving the forward-reserve allocation problem in warehouse order picking systems', Journal of the Operational Research Society **61**(6), 1013–1021.

Hackman, S. T., Rosenblatt, M. J. & Olin, J. M. (1990), 'Allocating items to an automated storage and retrieval system', IIE transactions **22**(1), 7–14.

Hollingsworth, B. K. (2003), Decision strategy to minimize replenishment costs in a distribution center with forward reserve storage, PhD thesis, Ohio University.

North, M. J. & Macal, C. M. (2007), Managing business complexity: discovering strategic solutions with agent-based modeling and simulation, Oxford University Press.

Pawlewski, P. (2015), 'Simulation model to optimize picking operations in a distribution center', Przeglad organizacji (10), 37–43.

Tompkins, J. A., White, J. A., Bozer, Y. A. & Tanchoco, J. M. A. (2010), Facilities planning, John Wiley & Sons.

Van Den Berg, J. P. (1999), 'A literature survey on planning and control of warehousing systems', IIE transactions **31**(8), 751–762.

Van den Berg, J. P., Sharp, G. P., Gademann, A. N. & Pochet, Y. (1998), 'Forward-reserve allocation in a warehouse with unit-load replenishments', European journal of operational research **111**(1), 98–113.

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

Walter, R., Boysen, N. & Scholl, A. (2013), 'The discrete forward–reserve problem–allocating space, selecting products, and area sizing in forward order picking', European journal of operational research **229**(3), 585–594.

Appendix A

Product Types

Table A.1: Product Hierarchy in MKG warehouse

Product Type	**Description**
New product	Products that have not been stored in the DC before
Conveyable Fast	Fast-moving products which can be moved through the conveyor belt
Conveyable Slow	Slow-moving products which can be moved through the conveyor belt
Non-Conveyable	Products that cannot be moved through the conveyor belt due to their irregular physical characteristics such as odd shapes, lengthiness and heavy weight.
Small Products	These products are too small for the label applicator/scanner. Hence, they are moved in a large conveyable tray/box
Clothes	Items are picked and packed in a specific wave
Small Products - long	These are small products with length more than 55cm and are not stored in regular small bins
Pallet Products	Products, heavy and large, that are shipped as a pallet (rather than as a parcel)
Special Products internal	Products that require special picking procedure E.g.: Wooden decks, planks, fence, a stack of slides, stackable chairs
Wood Products External	Wet wood products, made of impregnated wood, are stored outside to maintain the humidity levels

Appendix B

Warehouse Configurations

B.1 Storage and Pallet Types

Table B.1: Storage and HU Bin Types

Storage bin types		HU Bin Types	
B2	Block pal 0,90m (h)	B09	Block 0,90m (h)
B6	Block pal 1,70m (h)	B17	Block 1,70m (h)
B7	Block pal 2,10m (h)	B21	Block 2,10m (h)
B8	Block pal 1,85m (h)	B85	Block 1,85m (h)
E2	Euro pal 0,90m (h)	E09	Euro 0,90m (h)
E6	Euro pal 1,70m (h)	E17	Euro 1,70m (h)
E7	Euro pal 2,10m (h)	E21	Euro 2,10m (h)
E8	Euro pal 1,85m (h)	E85	Euro 1,85m (h)

B.2 Warehouse Layout

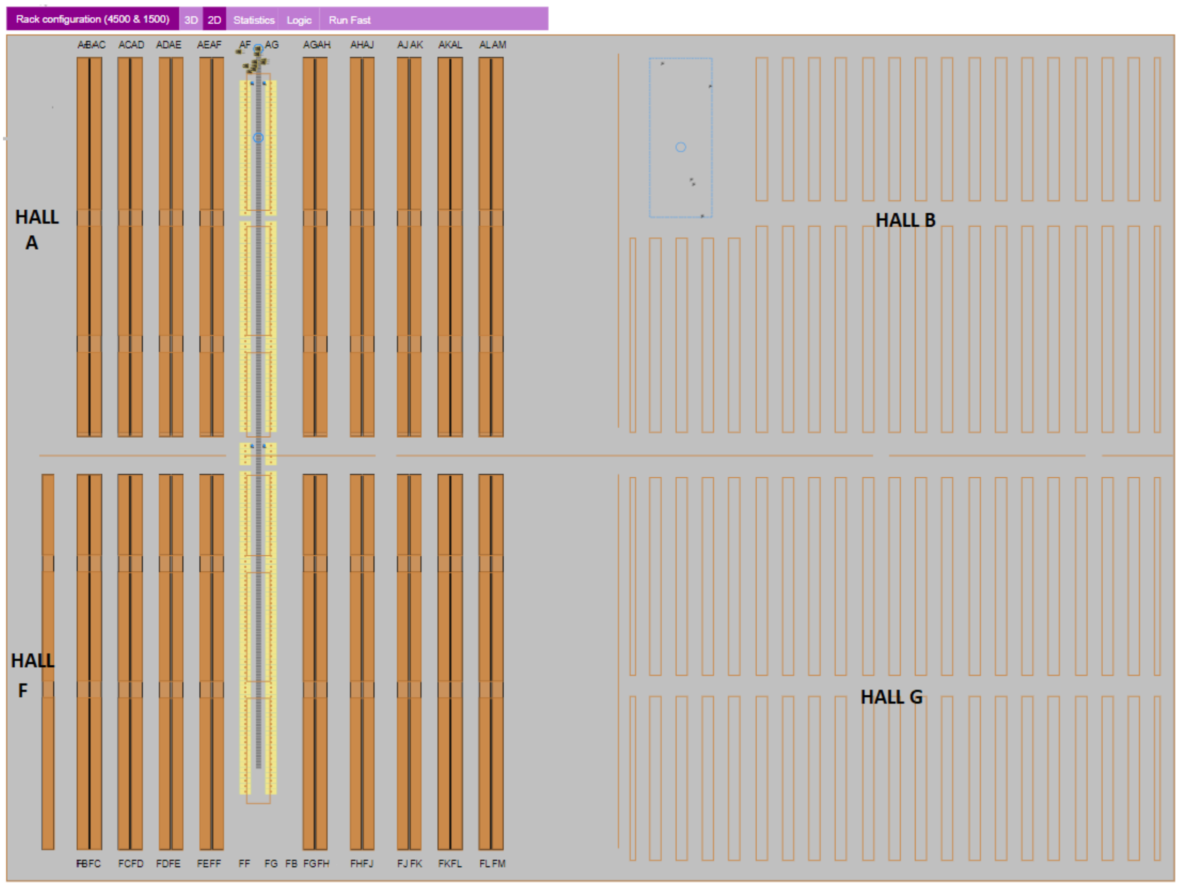


Figure B.1: 2D representation of MKI warehouse in AnyLogic